The NASA Carbon Monitoring System Phase 2 Synthesis: Scope, Findings, Gaps and Recommended Next Steps

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Abstract

Underlying policy efforts to address global climate change is the scientific need to develop the methods to accurately measure and model carbon stocks and fluxes across the wide range of spatial and temporal scales in the Earth system. Initiated in 2010, the NASA Carbon Monitoring System is one of the most ambitious relevant science initiatives to date, exploiting the satellite remote sensing resources, computational capabilities, scientific knowledge, airborne science capabilities, and end-to-end system expertise that are major strengths of the NASA Earth Science program. Here we provide a synthesis of "Phase 2" activities (2011-2019), encompassing 79 projects, 482 publications, and 136 data products. Our synthesis addresses four key questions: What has been attempted? What major results have been obtained? What major gaps and uncertainties remain? and What are the recommended next steps? Through this review, we take stock of what has been accomplished and identify future priorities toward meeting the nation's needs for carbon monitoring reporting and verification.

Keywords: carbon, monitoring, MRV, remote sensing

1. Introduction

Anthropogenic emissions of greenhouse gasses are the highest in history, and changes in the Earth's climate are having widespread impacts on both natural and human systems. In response, local, state, national, and international policies are in discussion and under development to reduce greenhouse gas emissions in the future. Foundational to these efforts is the scientific ability to accurately measure, and model, carbon stocks and fluxes throughout the Earth system and across a range spatial and temporal scales.

Initiated in 2010, a congressional appropriation directed NASA to initiate work towards a Carbon Monitoring System (CMS) and provided specific guidance. The approach NASA developed in following these directions emphasized exploitation of the satellite remote sensing resources, scientific knowledge, and end-to-end system expertise that are major strengths of the NASA Earth Science program. The approach also took into account data and expertise that are the domain of other U.S. Government agencies and anticipates close communications and/or partnerships with those agencies and their scientific and technical experts. Additionally, it laid the groundwork for CMS-related applications of current and future satellite sensors.

In Phase 1 (2010-2012), NASA's CMS activities were directed through NASA centers and involved two pilot studies and two scoping efforts (Hurtt et al. 2014a). The Biomass Pilot focused on quantifying the terrestrial vegetation aboveground carbon stock using consistent approach(es) and performing uncertainty analysis on its magnitude and spatial distribution. The initial emphasis was on production and evaluation of both local and U.S. -wide biomass products. The Flux Pilot produced an integrated emission/uptake product through a combination of space-based measurements of atmospheric carbon dioxide, carbon cycle models and assimilation systems, and information about the processes that couple the surface to the atmosphere. Scoping Studies focused on quantifying carbon in the oceans and the potential of NASA products to meet policy and decision-making requirements. In addition, more than a dozen Science Definition Team Projects were carried out. This work was synthesized in the Phase 1 Report (Hurtt et al., 2014a).

In Phase 2 (2011-2016), consistent with Congressional direction, NASA took steps to ensure substantial external (i.e., non-government) participation in CMS research by requiring individual projects to have greater than 50 percent of their funding directed to activities within external organizations. New projects were competitively selected to build upon initial efforts, with a large expansion in prototyping activities across a diversity of systems, scales, and regions, including research focused on prototype MRV systems for specific carbon management projects. In 2013, studies were added to advance MRV-relevant studies in support of REDD and REDD+ projects, and the U.S. SilvaCarbon program, using commercial off-the-shelf technologies. Selections in 2014 included studies to improve the CMS biomass and flux products and to conduct new MRV-relevant projects at local to regional scales, including several state-level biomass mapping projects within the U.S. and projects to quantify carbon in coastal ecosystems relevant to "blue carbon" objectives of reducing carbon emissions by conserving and sustainably managing a coastal carbon sink. In 2014, a congressionally mandated report documented NASA's approach to MRV (Hurtt et al. 2014b). The report summarized progress to date within the Caron Monitoring System project and described NASA's longer term strategy for CMS and its vision regarding NASA's role in MRV. In 2015 and 2016, project selections continued to advance biomass mapping efforts, flux quantification, and blue carbon mapping. Throughout, work was conducted to improve the characterization of errors and uncertainties in existing products and to engage stakeholders, identify their needs, and seek inputs on the value of CMS prototype products.

In all, during Phase 2 NASA supported 79 projects prototyping carbon monitoring activities around the world, in every major component of the Earth system, and linked to a diverse set of stakeholders and applications across a variety of domains. The effort represents one of the largest and most ambitious collections of applied carbon monitoring research created around the world. The goal of this paper is to synthesize the results from all completed Phase 2 projects into summary findings relevant to the program and the broader scientific community.

2. Methods

The scope of this report includes all CMS Phase 2 projects, publications, and archived data products as of August 2021. This included all projects initiated between 2011-2016 and completed as of this report.

To conduct the synthesis, we reviewed the CMS products hierarchically first within theme, then by theme, and finally at the initiative level (Fig. 1). More specifically, we collected a comprehensive set of all projects and their resulting publications and archived datasets and stakeholders (Fig. 2). To organize the analysis, each project, publication, and data product was assigned a primary theme based on the science being completed. Primary themes included: Land Biomass, Atmospheric Flux and Methane, Stakeholder, and Oceans/Wet Carbon. For each product, we also analyzed important metrics including domain, resolution, citation, downloads, and Application Readiness Level (ARL).

ARL is an index adapted from the NASA Technology Readiness Levels (TRLs) in order to track and guide application efforts of NASA funded projects such as those under the CMS program. The levels range from 1- basic science to 9- in mature and in operational use. These levels are used as a communication tool to give a clear picture of the current and projected “readiness” of each CMS projects’ involvement in decision-making and operational platforms. Products are assigned ARL levels by the Principle Investigator annually, and change as the products mature and are used in different ways by stakeholders. We measure the change in product maturity by comparing the ARL level at the start of the project to those at the end.

A subset of experts was then assigned to each of the primary themes to review the products in that theme and developed detailed findings centered around four key questions:

- What have NASA-CMS projects attempted in Phase 2?
- What major results and findings have been made?
- What major gaps and uncertainties remain?
- What are the recommended next steps?

The findings were then further aggregated to initiative level. Finally, feedback was sought from the community during sessions at the CMS Science Team Meeting in November 2019 and at the AGU Fall Meeting in December 2019.

3. Results

First, a series of quantitative summary metrics were calculated to describe CMS projects, and products. These metrics are presented below.

3.1 Summary Metrics

In total, CMS Phase 2 consisted of 79 projects, and resulted in 482 publications and 136 data products (Table 1). Biomass represented the largest theme, with 37 projects, 252 publications and 59 archived data products. Atmosphere Flux was second largest and had 33 projects, with 164 publications and 60 data products. Wet Carbon/Ocean had 7 projects, 63 publications and 17 data products. Stakeholder has 2 projects, 3 publications, and no data products.

Projects covered a wide range of geographic domains (Fig. 3). There were 22 projects with a global domain. Additional regional projects increased the total number of projects unevenly in different areas around the world. In Southeast Asia, Indonesia, South Africa, and South America an additional 1-5 regional projects produced a total for those regions of 23-27. The highest concentration of projects were focused on North America with 29 total projects and the U.S. with 39 total projects.

Archived data products provide a more detailed measure of data availability around the world (Fig. 4). Similar to the project level map, the data product coverage is uneven around the world and has the highest concentration over North America and the U.S. Additional product coverage over S. Africa, China, and India were primarily more local in focus. Investigating these patterns further, there were significant differences between Biomass and Flux products in terms of coverage (Table S1-S3). Flux products tended to represent a larger domain, with 50% (30/60) providing global coverage and fewer at all smaller domains including 17% (10/60) local. In contrast, Biomass products tended to represent smaller areas, with 46% (27/59) local, and only 8% (5/59) global. Likewise Ocean/Wet carbon products tended to be even more clustered in small domains, with 88% (15/17) at local or subnational scale, and 12% (2/17) global.

Spatial resolution varied by domain size and by theme (Fig. 5, Table S4). Flux products tended to have relatively coarse resolution with 82% (49/60) >1 km. Biomass products tended to have higher spatial resolution with 83% (49/59) <=1 km. As expected, there was generally an inverse relationship between domain size and spatial resolution consistent with these differences, with local scale products (e.g. Biomass) tended to have higher spatial resolution, and larger domain products (e.g. Flux) tended to have coarser resolution.

The temporal domain of products varied and spanned a range of pre-1960 to post-2060 (Fig. 6). The majority of products were focused on the recent past, with 82% (111/136) of CMS products covering the period 2000-2020, 15% (21/136) extending pre- 2000, and 3% (4/136) of products extending post-2020. Biomass had 75% (44/59) covering the period 2000-2020, 24% (14/59) products extending pre-2000 and 2% (1/59) post-2020. Flux had 85% (51/60) covering 2000-2020, 12% (7/60) products extending pre-2000, and 3% (2/60) post-2020.

The distribution of ARL and ARL change was calculated for Phase 2 products as a measure of application readiness and change in application readiness (Fig. 7, Table S5). The distribution of ARL values followed a modal distribution, with the most common ARL values in the intermediate range of 5-6 (51), and many fewer examples at beginning ARL 1-2 (11), or most mature status ARL 8-9 (15). All products experienced maturation during the period of development. The distribution of ARL change (Final ARL- Initial ARL) followed a decreasing function, with the largest category of projects increasing 1 ARL value and steadily declining to those advancing a full 8 ARL values over the project.

Stakeholders are defined as users actively engaged in CMS science projects. There were 132 different stakeholders working with CMS scientists in Phase 2 representing different types of organizations, science themes, and nationalities (Fig. 8). CMS projects engaged stakeholders from a wide variety of organizational types, with the most common types being federal government (15%), Company (15%), Non-Governmental Organization (15%), State Government (14%) and University (14%). Additional stakeholders represented Local government (6%), Research Institutes (6%), Intergovernmental Organizations (3%), Media (2%), Museums (1%) and Other (9%). Stakeholders also represented different science themes, with Biomass accounting for 53%, and Flux 30%, and MRV 17%. Stakeholders also represented different nationalities, with U.S. 73%, and followed by a variety of other countries each <=5%.

3.2 Thematic

Qualitative results were synthesized at the thematic level. These results are presented below and in Table form in Supplementary Material (Tables S6-S11).

3.2.1 Biomass

Tracking plant biomass in terrestrial ecosystems is an essential component of carbon monitoring systems. Biomass has been a focus of the NASA CMS since the program's inception, and many CMS projects have advanced our understanding of methods to map, track changes over time, characterize uncertainties in biomass estimates and project future storage potential. In addition, from these results CMS projects have been able to improve our understanding of the controls on biomass accumulation and loss in natural and managed systems.

Methodologically, CMS projects have shown that biomass mapping is achievable at multiple scales, and that such mapping is defensible in the context of MRV and international carbon programs such as REDD+. Mapping is possible through a combination of lidar, optical data, radar data, forest inventory data, and emerging statistical methods (Deo et al. 2016, 2017, Duncanson et al. 2015, Huang et al. 2015, 2017, 2019, Gu et al. 2016, Kennedy et al. 2018, Treuhaft et al. 2017, Xu et al. 2018, Zhang et al. 2014, Montesano et al. 2013, Simard et al. 2019, Babcock et al. 2015, Alonzo 2018, Babcock et al. 2016, 2018, Lagomasino et al. 2015, Thomas et al. 2018, Rappaport et al. 2018, Junttila et al. 2013, Saarela et al. 2018, Patterson et al. 2019, Tyukavina et al. 2013, Potapov et al. 2014, Swatantran et al. 2016, Fekety et al. 2018, Bullock et al. 2020, Arevelo et al. 2020; Fig. 9). In particular, many CMS projects have advanced the statistical tools needed to make such mapping defensible (Cooke et al. 2016, Datta et al. 2016, Finley et al. 2013, 2014, 2017, Reimer et al. 2016, Babcock et al. 2018, Montesano et al. 2013, Saarela et al. 2018, Patterson et al. 2019, Olofsson et al. 2020). **I**mportantly, these new methods are also highly generalizable and can also provide quantitative assessments of product uncertainties. In addition, the work has been conducted across a range of diverse ecosystems, and are applicable to new space-borne lidar missions such as GEDI (Duncanson et al. 2019, Healey et al. 2012, Patterson et al. 2019).

CMS studies have also contributed significantly to our understanding of the patterns of biomass, drivers of biomass change, and storage potential in vegetation and the soil. For example, human-caused forest disturbance (deforestation and degradation) remains the key driver of biomass and carbon loss in temperate and tropical forest systems, with fire, climate, and longer-duration stressors (drought, insect pests) playing an important role in some systems (e.g. boreal, savanna, peatland) (Baccini et al. 2017, Morton et al 2016, Pinage et al. 2019, Rappaport et al. 2018, Noojipady et al. 2017, Longo et al. 2016, French et al. 2014, Li et al., 2020; Cohen et al. 2016). There is evidence of recent diminishment of fire in regions of low- to intermediate- forest cover, perhaps because of transitions in human management associated with economic development, and increase in closed canopy forests (Andela et al. 2017). In global drylands systems, there is a strong link between precipitation and the rate and timing of carbon uptake and storage, but which is also mediated by plant adaptation strategies, including higher-than-expected investment in leaf-level photosynthetic machinery l in global drylands ecosystems, with possibly important implications for response to climate change. (Biederman et al. 2016, 2017, Hinojo-Hinojo et al. 2018). At the same time, increasing prevalence of prolonged drought periods may significantly outweigh any mediation by plant adaptation strategies leading to a chronic reduction in vegetation biomass in dryland systems, including the western U.S. Studies utilizing mechanistic ecosystem modeling have leveraged the high resolution lidar and optical data to move beyond traditional MRV and map both current stocks and future storage potentials for use in planning scenarios (Hurtt et al. 2019). The most recent results from these products are in active use in state-level carbon inventories and climate mitigation planning.

Despite these advances, gaps remain. Major areas of the world, including a diversity of different ecosystems, disturbance regimes, land-use activities, etc. have yet to be mapped or modeled or validated at high spatial resolution. Research has identified a key bottleneck and source of uncertainty in gridded products is accurate quantification and application of the allometric equations needed to create and scale-up reliable biomass reference data (Xu et al. 2018). Additionally, approaches to scale-up established methods to continental and global domains are needed. While the separate mapping of biomass and biomass change through disturbance has been successful, a more coordinated effort is needed to help reconcile issues related to biomass and disturbance loss and recovery in space and / or time. This spatial, resolution, and temporal mismatch in biomass and disturbance mapping efforts complicates the fusion of these datasets together to inform C management, including adequately capturing uncertainties related to these isolated mapping efforts. In addition, a major challenge for the mapping of biomass in some high-latitude or tropical regions, is the general lack of suitable measurements needed to train upscaling approaches. This includes both the training data (e.g. measurements of plant height, structure, biomass) themselves but also the remote sensing observations needed for scaling and creating the maps. Finally, despite better inclusion of methodological uncertainties in estimation, it is unclear how to advise practitioners when uncertainties from different sources disagree on the same measurement.

From these findings, challenges, and knowledge gaps, several important next steps emerge. Efforts must continue to expand biomass mapping over broad (continental to global) domains at a fine spatial resolution (appropriate to capture variability in both natural patterning and in human interventions that drive change), and linked to models for attribution of changes and future projections needed for planning. Validation frameworks are needed to assess accuracy at a variety of scales against high-quality reference data (e.g., Menlove and Healey 2020). In addition, clear protocols for the collection of measurements to use with biomass mapping (including clearly defining how to incorporate measurement uncertainties into scaling efforts) need to be provided to influence how large-scale measurements efforts (e.g. FIA) develop the essential datasets used for biomass accounting. While the goals for MRV are defensible, broad-scale biomass estimates and novel approaches should continue to be explored to help understand the influence of fine-scale variation on scaling efforts and how fine-scale patterns influence larger scale, but more coarse resolution, mapping efforts. These include the continued use of detailed in-situ measurements and validation of allometry using lidar tools (e.g. Xu et al., 2018), as well as the incorporation of other novel platforms such as unoccupied aerial systems (Alonzo et al. 2020) to provide both fine-scale, targeted (e.g. using UAS to fill in critical observation gaps) and spatially-extensive information on plant structure and biomass to inform scaling approaches or validate other products. Similarly, the temporal cadence of biomass mapping should increase to improve our understanding of biomass change, thus allowing better attribution of changes to drivers. At the same time, a tighter coupling of efforts between biomass and disturbance mapping should be explored as this will be essential for increasing the temporal frequency of biomass estimates and also ensure landscape changes are correctly accounted for. The incorporation of more model-driven biomass upscaling should also be considered, which would allow for the fusion of observation data and process models to infer biomass state based on measurements and mechanistic modeling of plant growth (Fer et al., 2018). In general, these improved maps of change must continue to be better integrated into process-based models and with tower-based flux observations. Throughout all of these steps, clearer definitions of product uncertainties are needed, particularly relative to the types of factors included within uncertainty estimates for different products.

3.2.2 Flux

Flux activities in CMS Phase 2 focused on developing new methods for estimating carbon fluxes, characterizing key sources of uncertainty, and deploying new measurements to support flux evaluation. CMS flux products represent both bottom-up (e.g. process models, inventories combined with land surface remote sensing data) and top-down (atmospheric inversion) approaches. CMS investigators have developed multiple observationally-constrained bottom-up estimates of the major flows of carbon including fossil fuel (Asefi et al. 2014, Gately and Hutyra 2017, Oda et al. 2018) and fire emissions (Andela et al. 2019) and land (Hardiman et al. 2017, Weir et al. 2021a) and ocean (Brix et al. 2015, Carroll et al. 2020, Gregg et al. 2017) carbon flux. They have also improved inverse methods that use atmospheric observations to infer surface sources and sinks with a focus on attributing net flux to underlying processes at both regional (Fischer et al. 2017, Graven et al. 2018, Hu et al. 2019) and global (Liu et al. 2017, Wang et al 2018) scales (Fig. 10). Phase 2 projects also improved characterization of major sources of uncertainty including atmospheric transport model errors (Diaz-Isaac et al. 2019, Brophy et al. 2019, Butler et al. 2020) and deployed both ground-based (Fischer et al. 2017, Graven et al. 2018) and aircraft measurements (Wolfe et al. 2018, Hannun et al. 2020) to validate local to regional scale flux estimates. CMS Phase 2 also included the first project designed to evaluate the consistency and completeness of CMS products for estimating global and regional carbon budgets.

CMS projects yielded a diverse set of results that represent an increased understanding of both anthropogenic and natural flux processes. These findings show that global inverse models that incorporate satellite CO_2 observations are able to reduce flux uncertainty and quantify the relative distribution of regional net fluxes (Liu et al. 2014, Wang et al. 2020). When combined with other types of observations (e.g. shorter-lived trace gasses, indicators of vegetation productivity), such models can provide additional information about specific flux processes including respiration, gross primary production, and fire emissions (e.g. Liu et al. 2017, Konings et al. 2019, Magney et al. 2019). Multiple studies focused on quantifying the impact of El Nino events on atmospheric CO2 and on understanding the regional mechanisms that control these changes in the tropics (Bowman et al. 2017, Y. Chen et al. 2017, Liu et al. 2017) and midlatitudes (Hu et al. 2019). CMS phase 2 projects also demonstrated the ability to constrain and validate anthropogenic emissions estimates on regional scales using a combination of in situ measurements and remote sensing data (Chen et al. 2016, Fischer et al 2017, Graven et al. 2018, Sargent et al. 2018]). During the COVID-19 pandemic, global data assimilation systems were able to detect the small decrease in global fossil fuel emissions and to evaluate independent country-level estimates of emissions changes (Weir et al. 2021b). Bottom-up datasets also yielded new insights into the key processes and trends driving flux changes across land (M. Chen et al., 2017, Andela et al. 2019, Fu et al. 2019, Bloom et al. 2020) and ocean ecosystems (Gregg et al. 2017, Carroll et al. 2020). This progress, particularly at global scales, supports the capacity building potential of CMS. Many global flux products provide detailed information for non-Annex I countries that may improve national level reporting mandated by the Paris climate accord.

In addition to demonstrating understanding of processes, many CMS projects focused on highlighting the observational and modeling priorities that are needed to further refine flux estimates. The availability of high-resolution, low-latency global flux and emissions datasets remains an unmet need in the atmospheric carbon monitoring community (Oda et al. 2018, Weir et al. 2021a). Though uncertainty quantification (UQ) methods have improved throughout CMS (e.g. Bousserez et al. 2015, Oda et al. 2019), atmospheric transport remains a sizable source of uncertainty for inverse estimates at both regional and global scales (Diaz-Isaac et al. 2019, Brophy et al. 2019, Butler et al. 2020). Many critical carbon cycle processes are poorly captured by climate models (Andela et al. 2019, Fu et al., 2019) despite research advances in recent years.

While Phase 2 CMS flux projects reflected progress in quantifying both human emissions and natural fluxes, many challenges remain. Large differences in bottom-up flux estimates persist despite incorporation of satellite data in land and ocean models (Ott et al. 2015). There is a lack of independent atmospheric data at appropriate spatio-temporal scales for evaluating fluxes (Wolfe et al. 2018), especially in the tropics. Though substantial improvements have been made over the past decade, satellite bias and coverage gaps limit both the accuracy (Basu et al. 2018) and spatial scale of top-down global fluxes (Wang et al. 2018). Regional top-down estimates, which can help improve the spatial scale of flux estimates in key regions like the United States where denser observations are available, are complicated by a lack of boundary condition information. Uncertainty estimates, a required element for all CMS products, are often difficult to interpret because of differences in the quantification method used by various projects. In addition to challenges that influence product quality, flux projects have also had more difficulty connecting with stakeholders than some other areas within CMS. Relevant factors include technical roadblocks like a lack of familiarity with scientific data formats among stakeholders, incompatibility between geographical boundaries and spatial resolution of models, and differences in scientific and policy-relevant carbon accounting definitions. In addition, most CMS research products have long latencies and irregular update schedules, which also limits relevance to stakeholder communities.

Progress made across individual CMS projects provides the opportunity for substantial advances in flux estimation in coming years. Quasi-operational flux modeling systems are reducing latency in flux estimates to support research and stakeholder communities. Better integration of regional and global modeling activities could help support more robust and reliable flux estimates across scales with improved characterization of uncertainties. Net flux estimates may also be improved through incorporation of observations from multiple satellites, allowing either a longer period of record for better understanding of interannual variability and trends (e.g. GOSAT and OCO-2) and/or denser observations in key regions (e.g. OCO-2 and GeoCarb). Integration of multiple types of observations that simultaneously constrain flux, stocks, and disturbance into dynamical data assimilation systems can improve consistency of flux products and improve their ability to yield policy relevant information. New observations that support evaluation of regional flux evaluation can improve confidence in flux estimates. Cross-project coordination is also critical in addressing several known gaps. Improving consistency in uncertainty methods of bottom-up CMS flux datasets would allow them to better inform top-down estimates and to improve quantification of top-down uncertainties. CMS also needs to work toward an integrated approach for engaging potential flux stakeholders, particularly at national and global scales where it is important for NASA and other government agencies to provide consistent, regularly updated, high-quality flux information.

3.2.3 Methane

CMS methane activities in Phase 2 focused on enabling the use of satellite observations of atmospheric methane to quantify and attribute emissions on local, regional, and global scales. The work involved strong collaborations with climate policy stakeholders including the California Air Resources Board (CARB), the US Environmental Protection Agency (EPA), Environment and Climate Change Canada (ECCC), the Mexican National Institute of Ecology and Climate Change (INECC), the Integrated Global Greenhouse Gas Information System (IG^3IS), and the Rocky Mountain Institute (RMI).

A major component of CMS methane activities has been the exploitation of GOSAT satellite observations (2011-present) to quantify methane emissions, the methane sink (mainly tropospheric OH), and their trends on the global scale (Maasakkers et al. 2019, Y. Zhang et al. 2021, Lu et al. 2021). Other GOSAT analyses have focused on North America (Turner et al. 2015, 2016, Sheng et al. 2018a, Maasakkers et al. 2021), and on tropical wetlands (Parker et al. 2018). CMS investigators have conducted atmospheric measurement campaigns to quantify methane emissions on urban/regional scales and support satellite observations. This has involved evaluation of commercial solar-viewing shortwave infrared (SWIR) spectrometers with the TCCON satellite validation standard (Hedelius et el. 2016, 2017), and application of these spectrometers to study emissions in Boston (McKain et al. 2015) and from dairies (Viatte et al. 2017). It has also involved inversion of ground-based network observations to quantify emissions in the Los Angeles Basin (Yadav et al. 2019), inversion of NASA SEAC^{4}RS aircraft observations to quantify emissions in the Southeast US (Sheng et al. 2018b), and aircraft campaigns using the AVIRIS-NG imaging spectrometer to map methane plumes from point sources and infer emissions (Duren et al. 2019, Cusworth et al. 2020a, Thorpe et al. 2020). Combined analysis of satellite, aircraft, and surface observations over the Los Angeles Basin demonstrated the power of the integrated observing system (Cusworth et al. 2020b), as did the combined analysis of multiple satellite data streams to quantify emissions from a gas well blowout (Cusworth et al. 2021a).

Inversions of satellite data to infer methane emissions require high-quality, spatially resolved emission inventories to serve as prior estimates. Developing such inventories has been a priority for CMS and has focused globally on wetlands (Bloom et al. 2017, Poulter et al. 2017, Tian et al. 2015a, B. Zhang et al. 2017, Treat et al. 2018), rice (Zhang et al. 2016), livestock (Wolf et al. 2017), and fossil fuels (Scarpelli et al. 2020a). It has also involved spatial disaggregation of national inventories for the US (Maasakkers et al. 2016) and Mexico (Scarpelli et al. 2020b). A detailed map of methane-emitting infrastructure has been developed for the Los Angeles Basin to guide atmospheric measurements (Carranza et al. 2018).

Another priority for CMS has been to enable the next generation of satellite observations of methane. The new high-density TROPOMI satellite observations have been used to infer methane emissions on the ~10 km scale (Varon et al. 2019, Zhang et al. 2020, Shen et al. 2021). Studies have determined the combined value of thermal and shortwave IR (TIR+SWIR) measurements to resolve lower-tropospheric methane (Worden et al. 2015) and infer trends in tropospheric OH (Y. Zhang et al. 2018). CMS has contributed to specifications for future geostationary instruments such as GeoCARB and GeoFTS to constrain methane emissions from the regional scale down to the scale of individual facilities (Cusworth et al. 2018, Sheng et al., 2018b, Turner et al. 2018). CMS has been a motor for developing the power of GHGSat and imaging spectrometers such as PRISMA and Sentinel-2 to observe point sources of methane (Cusworth et al. 2019, 2021, Varon et al. 2018, 2019, 2020, 2021).

CMS methane activities have yielded a number of important results. They have established that inundation and ecosystem respiration are major drivers of variability and trends in methane emissions from wetlands, as shown by GOSAT observations (Parker et al. 2018) and biogeochemical models (Zhang et al. 2017, Bloom et al. 2017, Poulter et al. 2017). Wetland models with low methane to temperature sensitivity generally agree better with satellite observations (Ma et al. 2021). Through the development of spatially-resolved national inventories and their application to inversion of satellite observations, CMS has shown that emissions from the oil sector are underestimated by a factor of 2 in the national inventories for the US (Maasakkers et al. 2021) and Mexico (Shen et al. 2021). On a point source level, CMS investigators have achieved better understanding of the role of 'super-emitters' in contributing disproportionately to state and national methane emissions (Duren et al. 2019, Varon et al. 2019, 2021, Cusworth et al. 2021b) and have identified the underlying processes for landfills (Cusworth et al. 2020a) and gas storage facilities (Thorpe et al. 2020). Results from these point-source CMS studies were shared directly with industry and agency stakeholders who conducted follow-up site visits with surface sensors to verify and further refine source attribution. In roughly 50% of those cases, facility operators indicated that the confirmed super-emitters were fixable and a subset of those were repaired. The net magnitude of mitigated methane emissions from those studies is currently being reviewed.

Better understanding has also been achieved of the drivers of global methane trends over the past decade, as illustrated by Fig. 11. Inversion of GOSAT data suggests that tropical livestock could be a major driver for the decadal trend, while wetlands may contribute to the acceleration of the trend since 2016 (Zhang et al. 2021). Changes in OH concentrations could greatly contribute to the interannual variability of methane (Turner et al. 2017) though probably not to the decadal trend (Y. Zhang et al. 2021).

Major gaps remain in our understanding of methane emissions. There is considerable uncertainty in quantifying wetland emissions and how these emissions contribute to the global methane trend. This includes uncertainties in the carbon respiration rate (Bloom et al. 2017), inundation dynamics (Parker et al. 2018), and contributions from the non-growing season (Treat et al. 2018) Improved biogeochemical models for methane emission from wetlands are needed (Xu et al., 2016). The factors contributing to the global trend in atmospheric methane over the past decade are also still open to debate.

The next several years offer considerable opportunity for improving our ability to use satellite data for quantifying methane emissions on all scales (Jacob et al. 2016). Planet and Landsat products can enable better understanding of land surface characteristics to improve our ability to quantify wetland methane emissions. TROPOMI observations should be transformative for improving the capability of inversions of atmospheric methane to constrain the methane budget on global to regional scales. GeoCARB geostationary observations over the Americas should enable better quantification of emissions from South American wetlands. The emerging constellation of satellite instruments able to quantify point sources (GHGSat, PRISMA, S-2, EnMAP, EMIT, MethaneSat, Carbon Mapper) opens up the possibility for operational leak detection and sustained emissions quantification at the scale of individual facilities. The ability to constrain global OH trends from satellite observations of methane should improve through exploitation of TROPOMI and CrIS data.

3.2.4 Marine, Freshwater and Wet Carbon

CMS projects have contributed to various efforts to better characterize the role of oceans and coastal interfaces in global carbon cycling. Some of this work has been summarized in the Second State of the Carbon Cycle Report (USGCRP 2018) as well as published papers on the North American coastal carbon cycle (Fennel et al. 2019) and the carbon budget of Eastern North America (Najjar et al. 2018). Additionally, Benway et al. (2016) produced a synthesis of current information about coastal carbon budgets and provided a series of recommendations for future research.

Some CMS projects have considered the nature of coastal margins as boundaries to the continental carbon cycle. Related to this is improved observation and modeling of lateral transport of terrestrial carbon and nutrients into the watershed and ultimately to coasts (Liu et al. 2013, Lohrenz et al. 2013, Ren et al. 2016, Ren et al. 2015, Tao et al. 2014, Tian et al. 2015b, Tian et al. 2015c, Tian et al. 2020, Xue et al. 2013; Fig. 12). A key to understanding this important term is how land use and land cover along with other drivers such as human activity and climate-related changes affect lateral transport processes.

Considerable focus was given to the potentially large reservoirs of carbon biomass undergoing substantial change in sensitive coastal ecosystems. Both mangrove and tidal wetland ecosystems are critical coastal buffer zones and are undergoing rapid changes. CMS efforts include studies of mangroves (Fatoyinbo et al. 2018, Lagomasino et al. 2016, Lagomasino et al. 2015, Lee and Fatoyinbo 2015, Simard et al. 2019) and tidal wetlands (Byrd et al. 2018, Hinson et al. 2017, Holmquist et al. 2018a, Holmquist et al. 2018b, Hopkinson et al. 2012, Morris et al. 2016). Mangroves account for a substantial amount of carbon biomass and various CMS efforts examined Lidar-based algorithms for refining aboveground biomass estimates (Fatoyinbo et al. 2018, Lagomasino et al. 2015, Simard et al. 2019). Tidal wetlands also represent an important coastal carbon reservoir (Byrd et al. 2018, Holmquist et al. 2018a, Holmquist et al. 2018b, Hopkinson et al. 2012, Windham-Myers et al. 2018). CMS projects have also evaluated sources of methane and nitrous oxide emissions. This included examination of tidal wetlands and aquaculture sites (EPA 2019, Poulter et al. 2017, Zhang et al. 2017), as well as more comprehensive assessments over North America and globally (Tian et al. 2015a, Tian et al. 2012b, Tian et al. 2016, Xu et al. 2012).

CMS efforts have greatly expanded the information about oceans and coastal interfaces and their key role in global carbon cycling. Efforts such as the Second State of the Carbon Cycle Report (Fennel et al. 2019, USGCRP 2018) have provided an initial assessment of air-sea and land-ocean fluxes for North America. CMS investigators contributed to chapters covering Inland Waters (Ch. 14), Tidal Wetlands and Estuaries (Ch. 15), Coastal Ocean and Continental Shelves (Ch. 16), and Biogeochemical Effects of Rising Atmospheric Carbon Dioxide (Ch. 17). Coastal margins in North America act as a net sink of carbon. The North American Exclusive Economic Zone (EEZ) is estimated to be a net sink for carbon on the order of 160 $\pm$ 80 Tg C y^{-1} (Fennel et al. 2019). The estimated carbon input from land is 106 $\pm$ 30 Tg C y^{-1}. A global inventory of carbon dioxide fluxes in coastal margins influenced by large rivers (Cai et al. 2013) found that estuaries were a net source of CO_2 due to metabolism of terrestrial carbon entering these systems. In contrast, a global assessment of coastal areas influenced by large river plumes found that they were a net sink for CO_2. Considerable focus was given to the northern Gulf of Mexico and the Mississippi River plume, including extensive ship-based mapping and buoy measurements of pCO_2 (Cai et al. 2013, Guo et al. 2012, Huang et al. 2013, Huang et al. 2015a, Huang et al. 2015b) as well as model simulations using a coupled physical-biogeochemical model (Xue et al. 2014) and satellite-derived estimation of pCO_2 and air-sea flux of CO_2 (Lohrenz et al. 2018). The biological dynamics influencing carbon dynamics were considered by Chakraborty et al. (Chakraborty and Lohrenz 2015, Chakraborty et al. 2017), who explored the relationships between phytoplankton community composition and physiological properties of populations and relationships to environmental conditions. Other efforts have examined carbon properties in both the Gulf of Mexico and the Atlantic coast (Najjar et al. 2018, Wang et al. 2013).

Impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins. Changes in land cover and land use along with climate-related factors were determined to impact lateral movement of carbon and other materials through the watershed. Work by Tian et al. and his group utilized the Dynamic Land Ecosystem Model along with extensive satellite and ground-based observations to examine historical trends and patterns as well as modeled simulations of future scenarios under differing climate and atmospheric carbon forcing (Liu et al. 2013, Lohrenz et al. 2013, Ren et al. 2016, Ren et al. 2015, Tao et al. 2014, Tian et al. 2012a, Tian et al. 2015b, Tian et al. 2015c, Xue et al. 2013, Yu et al. 2018). Urban land conversion (Zhang et al. 2012, Zhang et al. 2014), livestock manure nutrient production (Yang et al. 2016), crop production (Lu et al. 2018), forest disturbance (Chen et al. 2013), drought (Chen et al. 2012), and large fires (Yang et al. 2015) were considered as significant factors in terrestrial carbon dynamics. More recent work has addressed factors affecting nitrogen loading to the Mississippi River basin (Lu et al. 2020, Tian et al. 2020). An additional carbon-related concern for coastal ecosystems is ocean acidification and its implications for coastal ecology and carbon cycling. Increasing ocean acidification may also reduce the buffering capabilities of coastal waters diminishing their capacity as carbon sinks (Fennel et al. 2019, Salisbury et al. 2015, Wang et al. 2013).

Consideration by CMS projects was given to productivity and influencing factors in the Upper Great Lakes (Fahnenstiel et al. 2016, Yousef et al. 2014). Information about primary productivity in the upper Great Lakes was significantly expanded through CMS efforts. Primary production in Lake Michigan was found to decrease over the 1998-2010 period, largely attributed to a decline in chlorophyll biomass as a result of the quagga mussel activity (Yousef et al. 2014). A comprehensive assessment of primary production was done for the upper Great Lakes for the period 2010-2013 (Fahnenstiel et al. 2016), thereby providing a baseline for future study.

Despite progress in understanding marine, freshwater and wet carbon dynamics, scientific uncertainties and priorities remain. These include continued refinement of terrestrial ecosystem models is needed to reduce uncertainties in carbon flux quantification. Improvements are needed in parameterization in areas such as in-stream organic production and transformation, as well as hydrological processes including effects of dams and rivers require further study. Constraining estimates of contributions by coastal margins and inland waters to continental and global carbon budgets requires improved assessments of exchange fluxes and the associated seasonal and interannual variability. While the amount of information has grown substantially, uncertainties represent a challenge because carbon is exchanged across multiple interfaces (land-coastal ocean, coastal ocean-open ocean, ocean-benthic, ocean-atmosphere). There is a need for improved characterization of spatial patterns and relationships to forcing, as well as assessments of these exchange fluxes and the associated seasonal and interannual variability. How coastal margins will be affected by changing climate forcing, sea level rise, and human impacts remains an important question. Tidal wetlands and mangroves represent large reservoirs of carbon and are important as potential sources of carbon dioxide and other greenhouse gases. Contributions of coastal margins to methane budgets are still poorly understood. Also, contributions of tidal wetlands and marshes to nitrous oxide budgets need to be examined. Tidal wetlands and mangroves have been identified as important sinks and sources, but still associated with significant uncertainties. Continental to global assessments are needed, but current knowledge is very limited regarding coastal margins as sources of methane or nitrous oxide.

Although considerable progress has been made in understanding contributions of coastal margins to global carbon, these contributions are still not well constrained, particularly with regard to seasonal and spatial patterns. There is a need for coordinated modeling and observations across the land-ocean continuum, including continued and expanded time-series observations to better discern temporal variability. Approaches should integrate observations, modeling and stakeholder needs (Fennel et al., 2019). There is also a need for better quantification of methane and nitrous oxide fluxes in different coastal types (e.g., river, estuary, tidal wetland, mangrove, etc.). Continued advancement of novel approaches such as remote sensing techniques for characterizing changes in carbon biomass and fluxes in coastal environments will be important for reducing uncertainty in these variables. Uncertainties in feedbacks need also to be addressed – how will future changes including climate, human impacts, and increasing atmospheric CO_2 affect efficiency of ocean uptake? Improved understanding of how coastal margins and associated carbon dynamics will change and what factors, including human activity, will influence that change will be important considerations for policy and decision-making.

3.2.5 Stakeholder

During Phase 2, stakeholder engagement accelerated at the federal, state, and local level, and with international partners. The CMS program funds basic and applied research that is created while engaging with a user community in a way that bridges carbon science and user communities to better serve societal needs (Brown et al. 2020; Fig. 13).

By connecting carbon cycle science research to stakeholders who use the data in their decision making, NASA CMS contributes to understanding and meeting the needs of the climate data user community. For example, Phase 2 produced novel data products on forest carbon product designed to meet state needs beginning in MD (Huang et al. 2015, Hurtt et al. 2019, Lamb et al. 2021a), and later expanding to the multi-state Regional Greenhouse Gas Initiative (RGGI) region (Tang et al., 2020, Ma et al. 2021, Lamb et al 2021b). New efforts on mapping and monitoring methane across California and other regions (Carranza et al. 2018) engaged the California Air Resources Board to identify and remove methane 'hotspots' across urban areas. Other stakeholders across a wide variety of CMS projects include Northwest Management Inc, The Nature Conservancy, Worcester Tree Initiative, Maryland Valleys Planning Council, World Resources Institute, BlueSource, Chesapeake Conservancy, US Forest Service, the

Environmental Defense Fund, the Sonoma County Agricultural Preservation and Open Space District, among many others.

Ensuring that critical information on carbon is used in day-to-day decisions and policy making by stakeholders such as governments, businesses, and institutions requires early engagement and frequent communication between the user and the producer of the information (Cash et al. 2006). The CMS program allows scientists to build mature relationships with stakeholders that result in greater success in moving a carbon cycle product from conceptualization to actual use within a decision-making context (Brown et al. 2021). It is only through funding a single individual who provides consistent engagement and builds relationships among and between the scientists and these institutions is CMS able to accelerate uptake of datasets in Phase 2 (Brown et al. 2020).

Major gaps from Phase 2 include the need for carbon products to be repeated, updated regularly, and for CMS to provide information that describes change through time instead of a single point in time. Change products would require standardization and repeat acquisition of input data, ongoing support of computing resources, access services, and for the policy relevance of the product to be clearly acknowledged and articulated. Gaps also include a relative lack of products such as products that describe the sensitive ecosystems of mangroves and urban forests, and products that link biomass to methane emissions. Economic studies are needed to demonstrate the value of these ecosystems and how information on them can be used in decision making in ways that may result in improved resilience and functioning (Horita et al. 2017). Economic analysis of the value of information may include data documenting impact of carbon cycle uncertainty (Cooke et al. 2016), and the costs and benefits of forest policy that incorporates carbon sequestration. For example, Lamb et al (2021b) describe how afforestation and reforestation in MD can provide both carbon sequestration potential and economic opportunity via forest carbon pricing verified through the use of geospatial products generated through the CMS program.

Recommendations include focus on evolving the CMS system to include more than biomass estimates, reconciling carbon stocks and fluxes, developing consistency across scales, quantifying movement and transport of carbon, attributing carbon emissions and sinks to respective sources, cross-sectoral accounting, uncertainty quantification, and providing redundancy in estimates (West et al. 2013). More data products are needed in new regions and new ecosystems, particularly supporting international initiatives where demand for decision support is increasing. Capacity to use carbon data products for people who are developing policy is a critical need, as Lamb et al. (2021a) demonstrated. With an improved understanding of the value of carbon and the alternative land uses, appropriate incentives and policies can be developed that increase the value of land use while sequestering more carbon.

CMS has developed a community of practice where scientists have learned how to do meaningful stakeholder engagement, the value of this engagement, and have learned through annual Science Team meetings and stakeholder workshops about applications of CMS products (Brown et al. 2020). This engagement by each funded project is one of the most novel parts of the CMS program and results in rapid prototyping and discovery of new carbon cycle data and models. By emphasizing in future funding opportunities the need for proposers to identify and engage with stakeholders before proposing, more rapid uptake of new carbon cycle products can be achieved (Brown et al. 2021). As Arnott (2020a) points out, funders of science are receptive to new ways of revisiting the 'social contract' for science so that co-production of knowledge can be prioritized. Ensuring CMS scientists prioritize relationships as well as producing products and writing papers is essential.

3.3 Initiative

CMS Phase 2 has engaged a large and diverse set of scientists and stakeholders in prototyping novel approaches to carbon monitoring in all major components of the Earth system (land, atmosphere, Ocean/wet carbon), for both biomass and fluxes, and over a variety of spatial (local to global) and temporal domains. The projects and their results have been described in multiple publications and synthesized at the thematic level above. Here they are aggregated up and synthesized at the Initiative level toward a systems perspective.

For Biomass, it is clear CMS has demonstrated thru multiple efforts that high-resolution mapping and modeling of forest biomass enabled by LiDAR/Radar and optical remote sensing is now possible across a range of systems, at multiple scales and ARLs, and is defensible in the context of MRV and REDD+. The advances thus far based largely on airborne data have yielded important applications in their own right and also paved the way for subsequent orbital missions such as GEDI and ICESAT2 and others. For Flux, atmospheric research and inverse modeling techniques have also qualitatively advanced and led to important new capabilities and findings for carbon. CMS has advanced two state of the art global flux systems, able to track sources and sinks and 3-D transport of carbon in the atmosphere. Importantly, regional networks of in situ and remote-sensing measurements of greenhouse gas concentrations have been shown capable of validating emission estimates. For Methane, satellite and aircraft observations have been demonstrated to usefully monitor methane emissions from the national/regional scale down to the scale of point sources. The resulting capabilities can be used in national inventories, and in the identification of superemitter point sources. For Wet carbon, research has quantified the importance of coastal margins as a sink of carbon – with high temporal and spatial variability, and that the impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins, and subsequently influence coastal carbon dynamics. Wetland and mangrove ecosystems have been shown to represent important reservoirs of carbon undergoing rapid change, and may also be important sources of methane and other greenhouse gases. Across all of these themes, and perhaps most importantly, CMS has demonstrated that addressing stakeholder needs and advancing science are mutually beneficial, with societal needs driving new science requirements and resulting in scientific results of high societal relevance.

Despite these advances, additional uncertainties and challenges remain. For example, the mapping of land biomass and biomass change, while promising, has yet to be accomplished with sufficient accuracy and resolution or attribution across all ecosystems, regions, disturbance regimes, and land-use classifications and time domains to meet stakeholder needs. Challenges remain to continue to improve atmospheric flux products and their connection with stakeholders. Net fluxes from atmospheric data do not have clear stakeholder. Long latency and intermittent availability impacts relevancy for stakeholders. Lack of independent data hampers flux validation. Technical issues - data formats, geographic boundaries, accounting definitions can be improved. Coastal margins are a substantial and highly variable signal in global carbon budgets, but this contribution is still not well constrained, particularly with regard to seasonal and spatial patterns. Limited work on aquatic ecosystems and oceans has been done to date. There is considerable uncertainty in quantifying wetland emissions and how they contribute to total national emissions and the global methane trend. Uncertainties in carbon respiration rate, inundation dynamics, non-growing season emissions all contribute. Different CMS studies suggest that wetlands, livestock, oil/gas exploitation, OH concentrations could all have contributed. Looking across projects, it is not clear how different estimates of uncertainty can be reconciled, or combined, or applied, or how/how well various CMS products could be combined into global system level assessments, and once realized how such advances could be maintained over time. There are many important science advances, partnerships, stakeholders, still needed to realize potential. New remote sensing assets, coordinated advances in computing and data, new partnerships and coordinated use of data from multiple sources/agencies, added stakeholders especially at the highest levels.

In the future, additional efforts are needed to prototype carbon monitoring capabilities to meet stakeholder needs across a full range of systems, scales, quantities, and stakeholders. It is unreasonable to assume that progress can be made evenly in all areas, or that there is a single system that can meet all of these needs. Future efforts should focus on building on successes, scale-up existing successful approaches, and initiate new activities in areas and domains most needed. Projects are needed that build upon airborne-based prototypes and incorporate new remote sensing datasets to improve and extend coverage of carbon monitoring capabilities, expand the coverage of forest carbon monitoring and modeling capabilities globally (GEDI, ICE-Sat2), and exploit the next generation of satellite observations to constrain methane fluxes in a way that serves stakeholder needs (GOSAT, TROPOMI, etc.). The impact on flux estimates from integration of multiple sensors needs to be assessed (OCO-2, GeoCARB, etc.). Projects should continue emphasis on validation, and improve and coordinate quantitative estimates of uncertainties to facilitate interoperability of products and their applications. To connect system components, integrated approaches for models and observations across scales, and across the land-ocean-atmosphere continuum, are needed. For maximum utility, an increased emphasis is needed on coupling models and observations to expand the time domain of products from contemporary periods, both backward to reach policy base year, and forward to include planning for climate mitigation. To ensure maximum relevance, continued emphasis on end to end stakeholder engagement, a hallmark of CMS, should be continued and expanded, and a plan must be developed to sustain key science advances and update products of high stakeholder importance.

4. Discussion

Over the past 10 years (2011-2021), NASA Phase 2 has supported 79 projects to completion prototyping innovative scientific approaches to carbon monitoring on land, atmosphere, and ocean, including fluxes between. The result is one of the largest collections of applied carbon monitoring research to date, evidenced by numerous publications, citations, products, and product downloads.

Key to this effort has been exploitation of the remote sensing and modeling expertise of NASA, collaboration with scientists and data products from other agencies, and the end-to-end focus on stakeholder engagement to meet societal needs for carbon. CMS projects have utilized both airborne and orbital remote sensing products, and have led the integration of these data with some of the most advanced models for both biomass and atmospheric fluxes.

In addition to products and metrics, there are numerous qualitative success stories that have emerged. The 2014 Farm Bill directed the US Forest Service (USFS) both to increase operational cooperation with NASA and to address monitoring of large areas of uninventoried forest in Interior Alaska. CMS has partnered with USFS to advance the national forest inventory in Alaska utilizing remote sensing over some of the most inaccessible areas. Over Maryland, high resolution forest carbon monitoring and modeling products have been implemented to meet the states mapping, monitoring, and planning needs, and serve as first in the nation utilizing remote sensing based assessment. Over wetlands, CMS products have pioneered mapping forest biomass and providing a global assessment of their carbon stocks in some of the most carbon sense ecosystems in the world. Internationally, CMS innovated a framework for forest MRV for other developing countries. CMS has also had multiple success stories in Atmospheric Flux. The carbon emissions from Indonesian Fires, of global importance, have been quantified and used in official IPCC reporting. Innovations quantifying methane flux have identified key point sources within the US, and nationwide lead to an update of US reporting of methane emissions. CMS also quantified land-ocean exchange of carbon in the Mississippi river basin, a key missing link in carbon accounting. Two global atmospheric flux systems provide state of the art synthesize and tracking emissions and fluxes worldwide.

Looking ahead, two key questions emerge. First, How can past advances of societal importance be sustained and updated and utilized? To meet these needs, all NASA CMS products are permanently archived and made freely available via Distributed Active Archive Centers (DAACs). Beyond that, additional efforts and partnerships are needed to support capacity building to utilize new data products, and to refresh and update important data products over time.

Next, what should be done to meet remaining needs for carbon monitoring? This report details a series of remaining science gaps and science next steps in both thematic areas and initiative wide. These recommendations need to be married to the stakeholder context, in which there is a growing need for carbon data at a variety of policy scales. Numerous cities have climate mitigation goals and carbon budgets, evidenced by the Compact of Mayors. More than 25 states in the US are members of the US Climate Alliance and have climate mitigation goals set in state policy. Most recently, the US has rejoined the Paris Climate Accord and has made new commitments in the Glasgow Pact. These different policy needs at different scales likely drive important differences in science requirements. These needs must be met with expanded and coordinated science advances designed to meet stakeholder needs in a flexible carbon monitoring system, or system of systems.

Despite NASA’s leadership in CMS, it is clear that NASA does not and cannot do this work alone (Hurtt et al. 2014b). The vast majority of CMS projects involve critical interagency collaborations with other federal agencies with complementary strengths, including USFS, NOAA, and others. There is tremendous opportunity now to strategically integrate and deepen these interagency collaborations further toward the development of the most robust carbon monitoring system capabilities to meet societal needs.

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Tables

Theme	Sub-theme	Number of projects	Number of Publications	Number of archived data products
Biomass	Land Biomass	37	252	59
Atmosphere/Flux	Global-Surface Atmosphere Flux	33	164	60
	Land-Atmosphere Flux			
	Methane			
Ocean	Ocean Biomass	7	63	17
	Ocean-Atmosphere Flux			
	Land-Ocean Flux			
Stakeholder	Decision Support	2	3	N/A
	MRV			
	Total:	79	482	136

Table 1. CMS Phase 2 projects, publications, and data products.

Figures

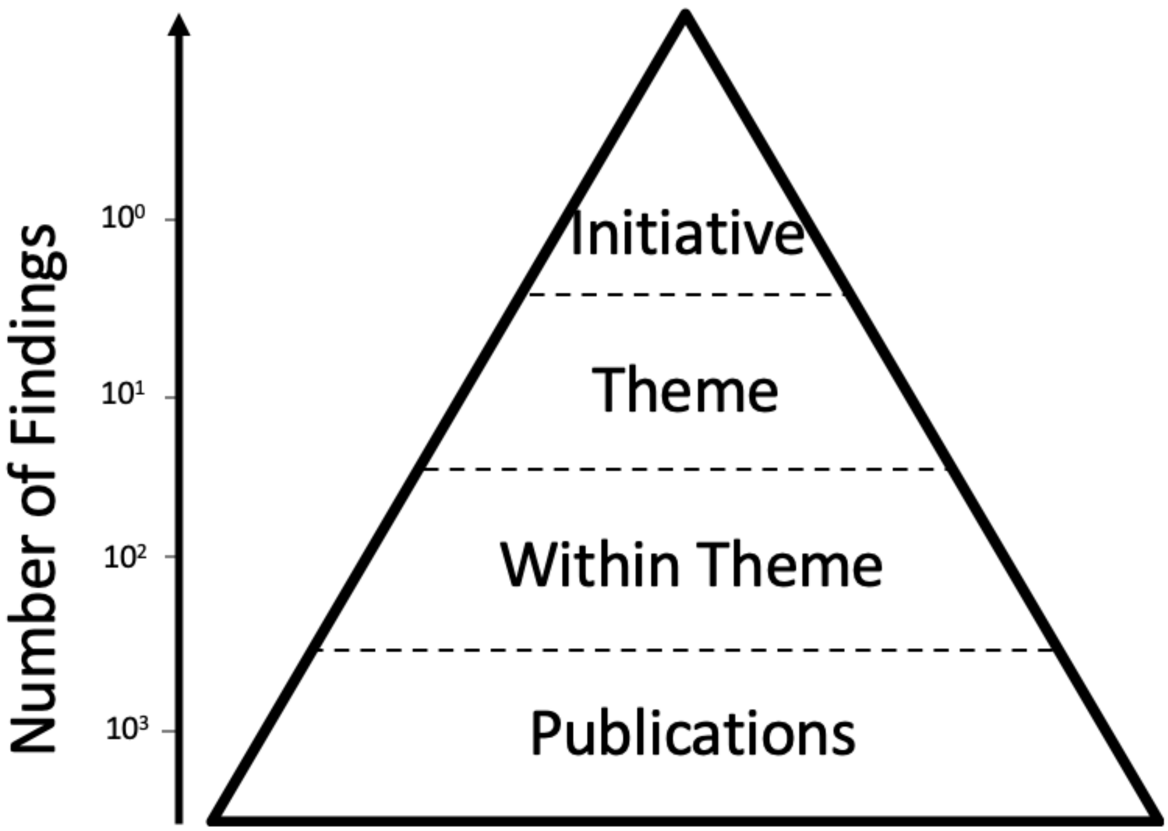

Figure 1. Conceptual diagram for synthesis of findings at multiple levels of organization. Results from publications can be aggregated by theme, which in turn can be aggregated to the initiative level.

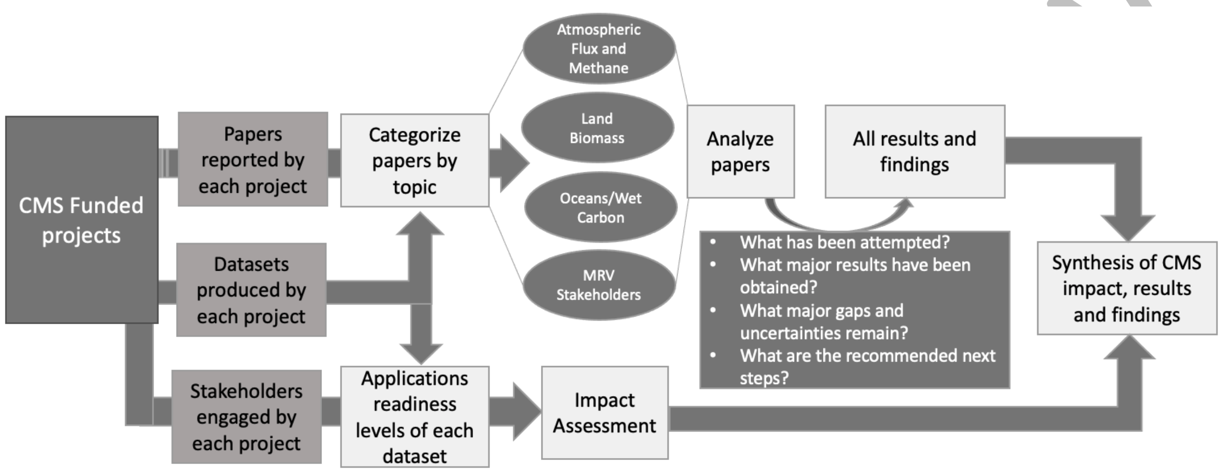

Figure 2. Summary of methods used to create CMS synthesis findings described in this paper.

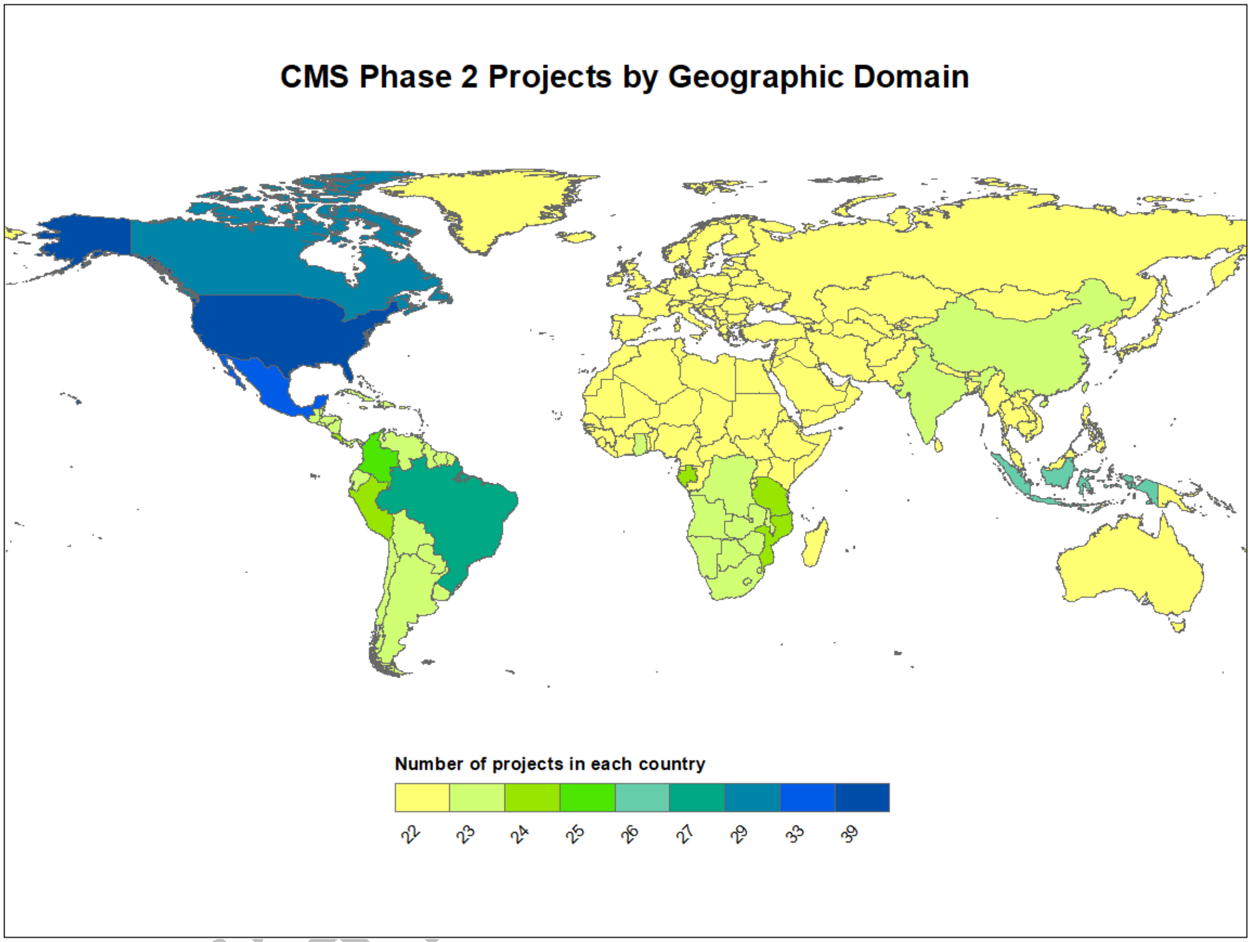

Figure 3. Number of CMS Phase 2 projects by geographic domain. There are 22 global projects and additional projects in various countries.

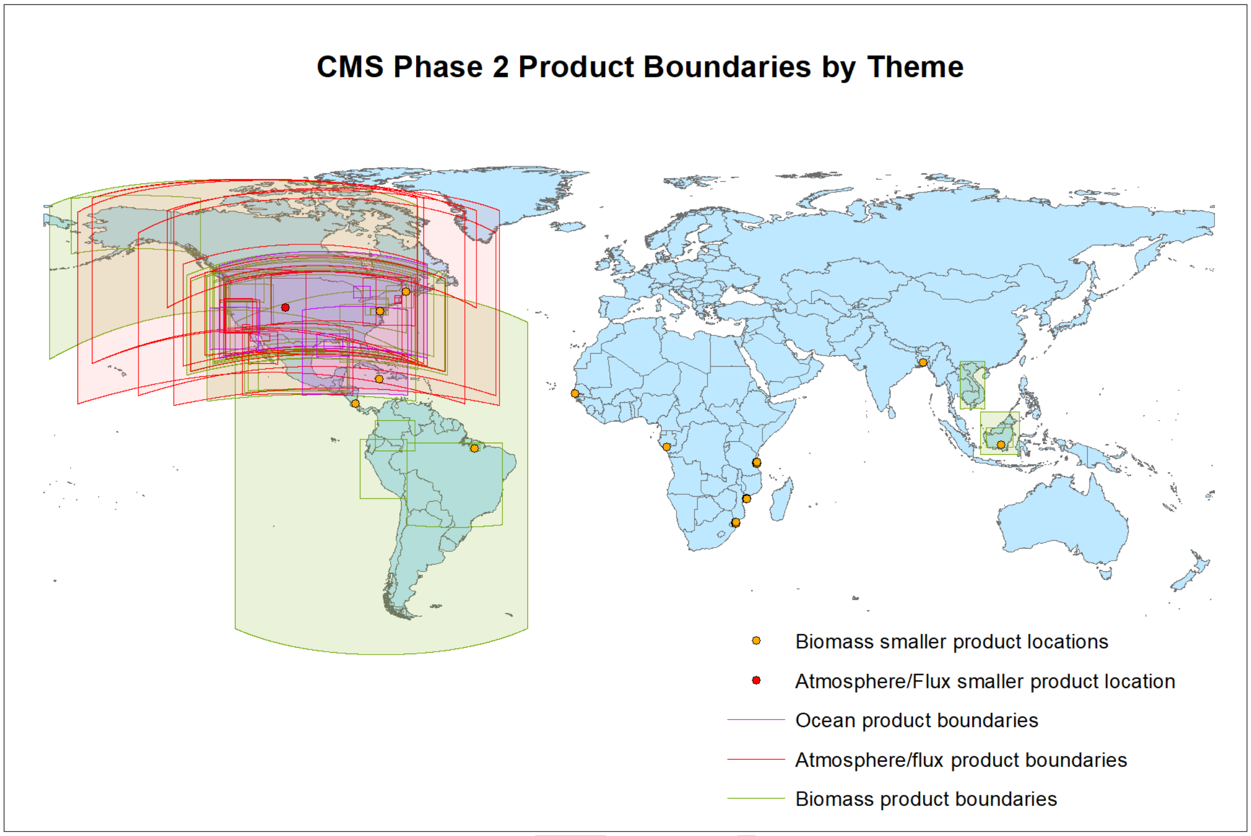

Figure 4. Number of CMS Phase 2 products (local and regional scale) by geographic domain and theme.
** Two projects with geographic domains of Southern Africa, and India and China produced no products for those regions.
**Global products (37) coverage not mapped.

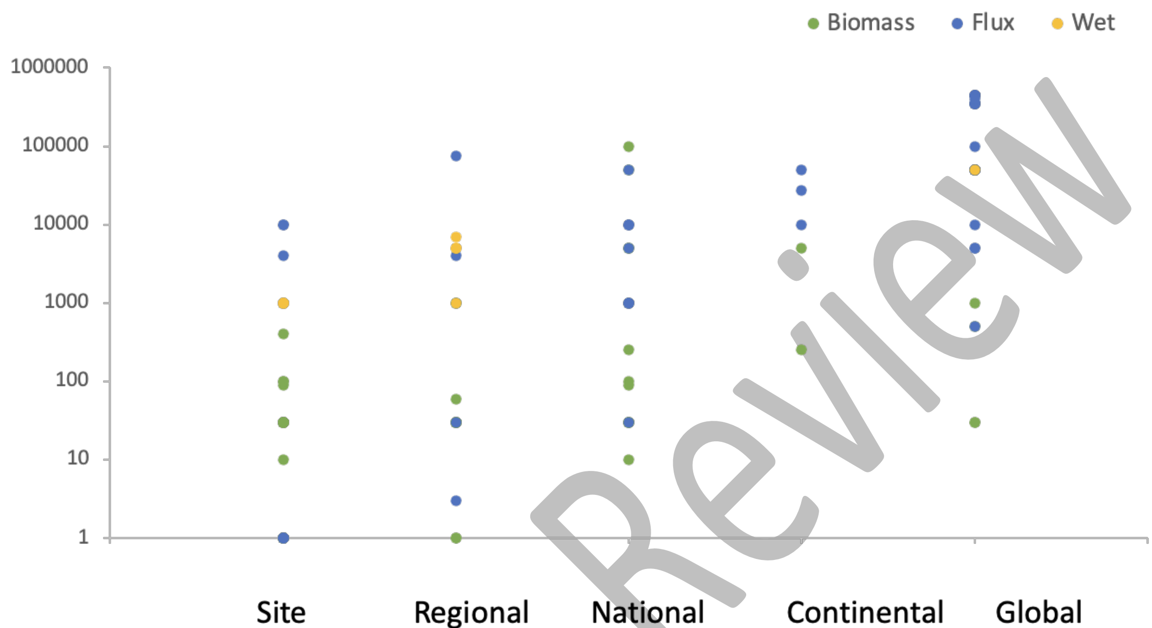

Figure 5. Spatial Domain and Resolution (m) of CMS Phase 2 products.

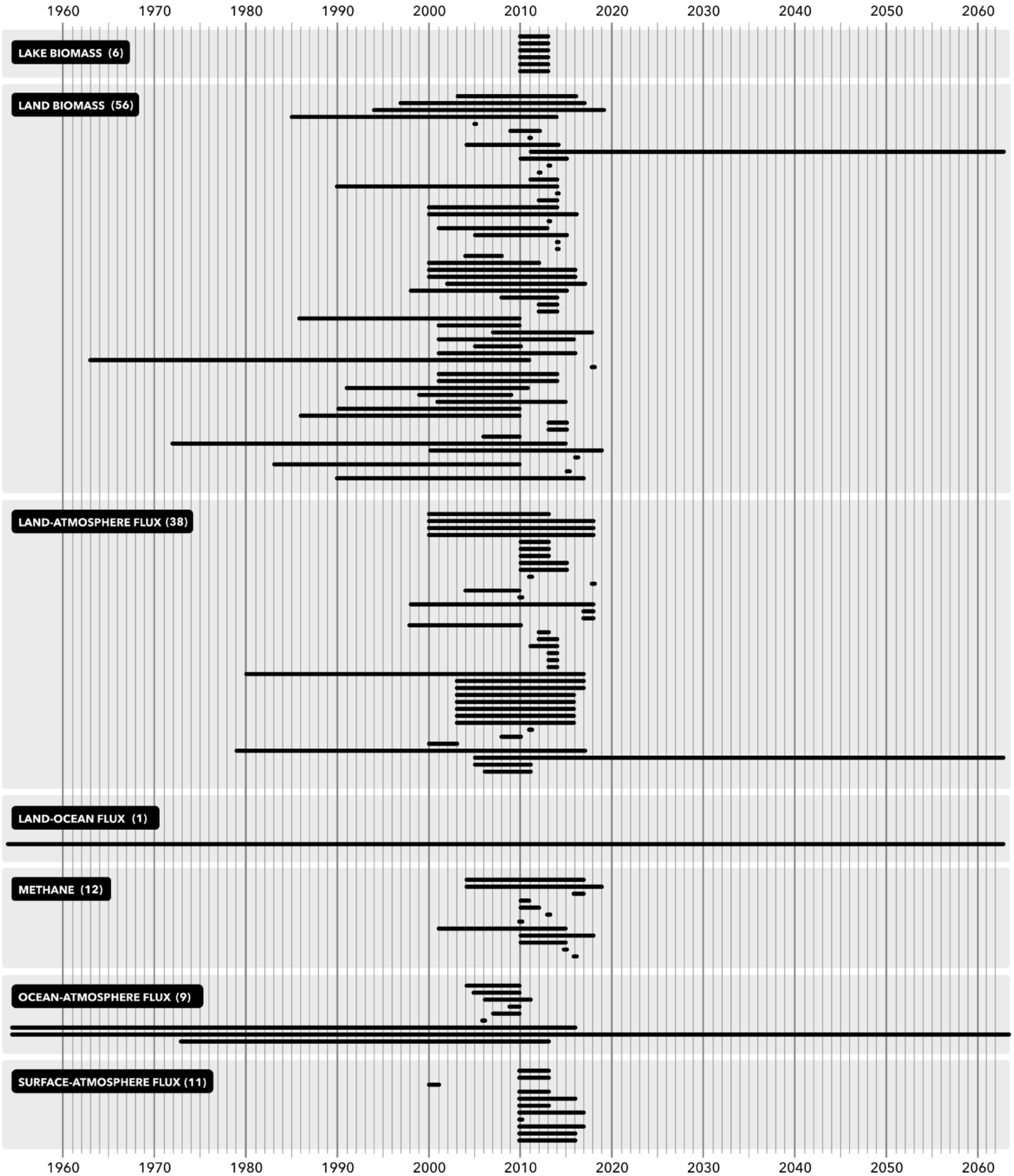

Figure 6. NASA-CMS Phase 2 Projects by time domain.

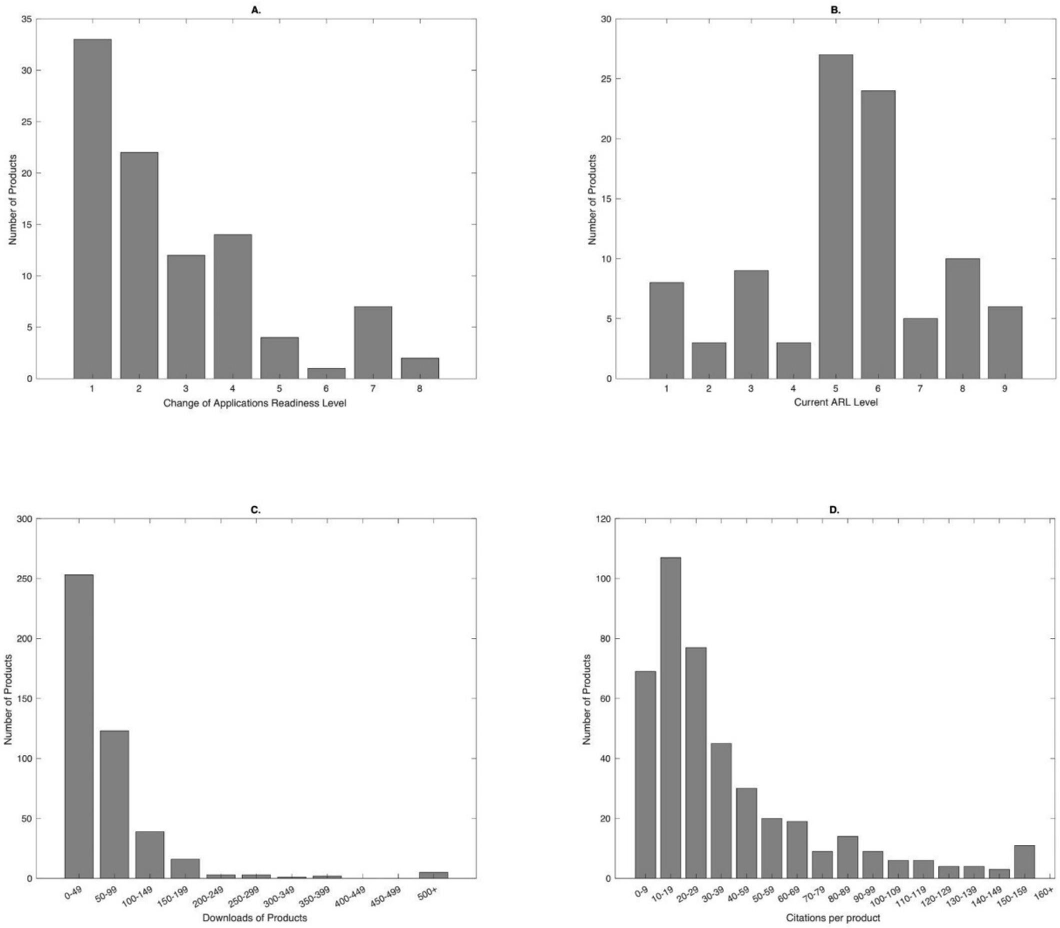

Figure 7. Product ARL and and Citations. A.) ARL change, B.) ARL current, C.) Downloads per dataset, D.) Citations of datasets 2011-2018.

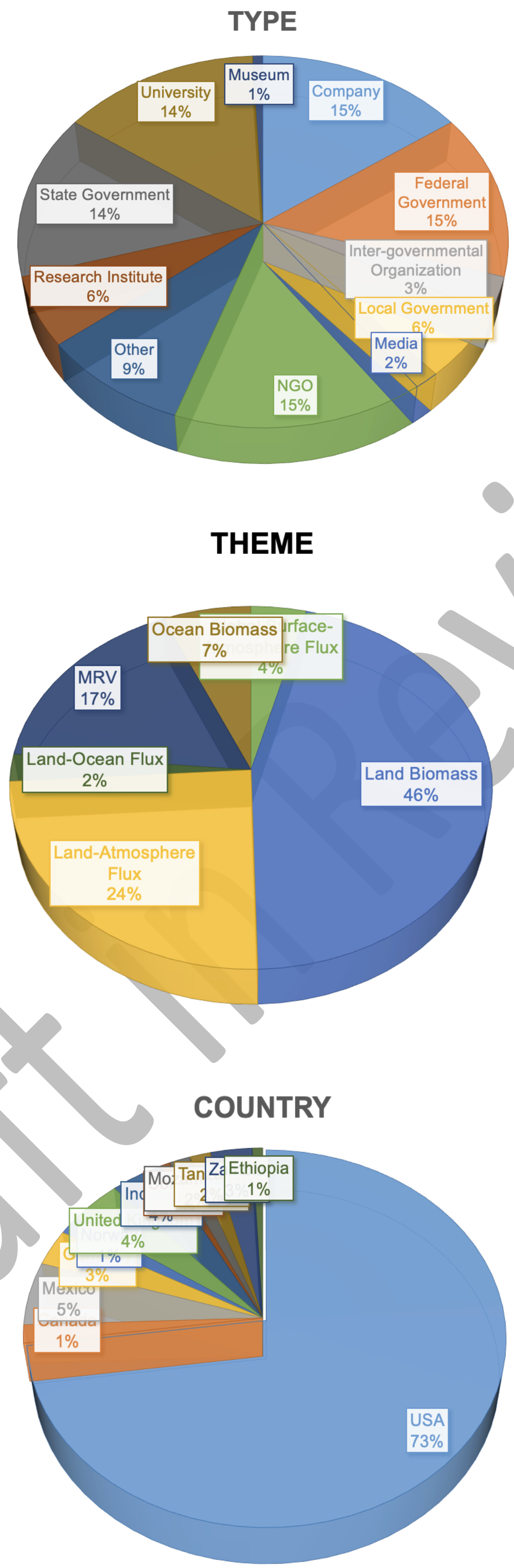

Figure 8. CMS Stakeholders by country, type, and theme.

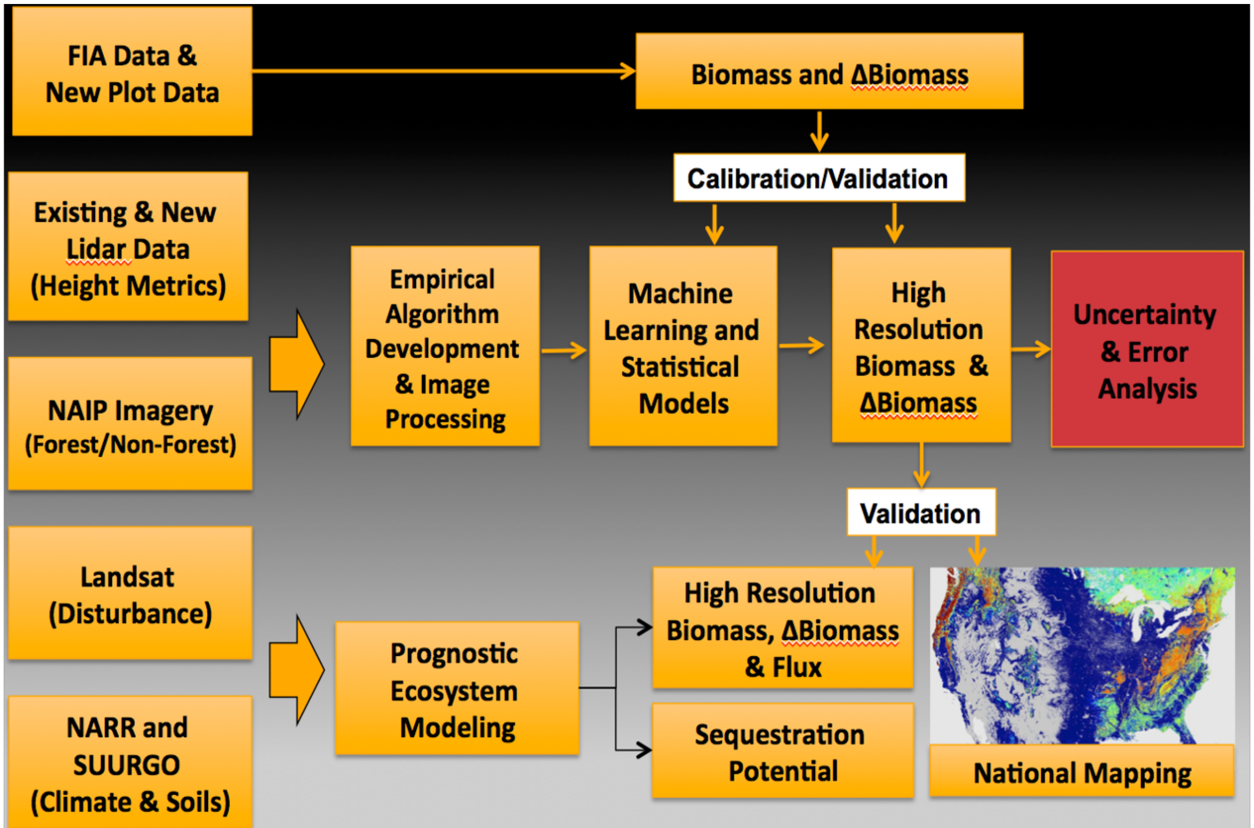

Figure 9. Example framework for utilizing lidar and optical remote sensing data together with field data to map above ground biomass, and model future carbon sequestration potential. Adapted from Hurtt et al. (2019).

CMS-Flux Framework

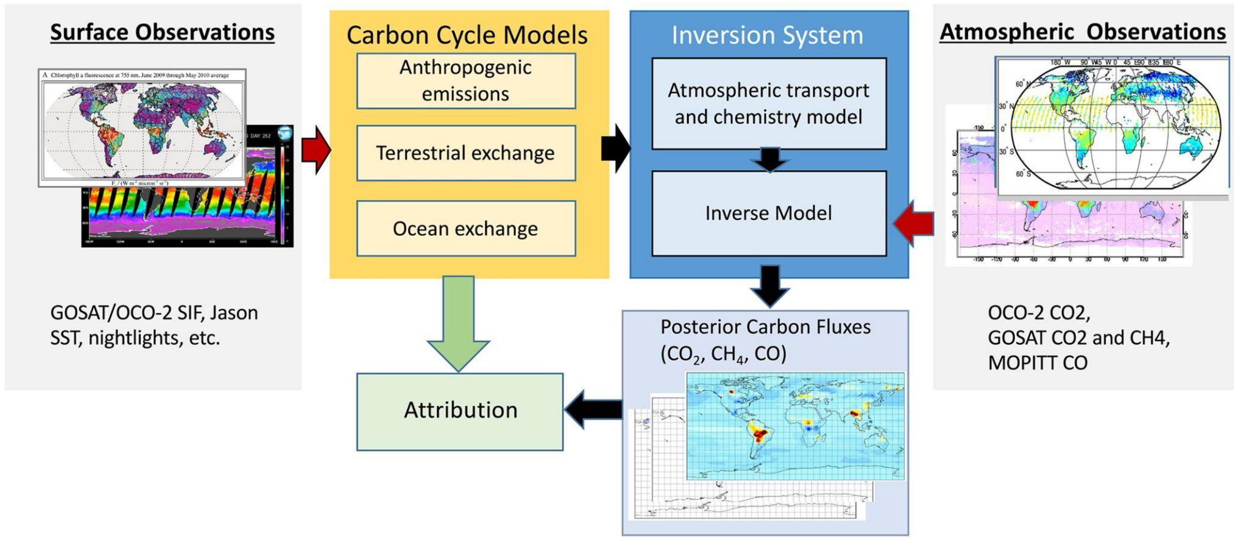

Figure 10. Carbon cycle inversion models, which infer surface-atmosphere flux from atmospheric measurements, have been a central component of CMS. Satellite observations of surface properties (e.g. ocean color, land surface reflectance, nighttime lights, fire radiative power) are used as input to data-driven models that provide a prior estimate of flux. These fluxes are transported through the atmosphere by chemistry and transport models. Atmospheric observations of CO_2 and other species are ingested by inverse models, which compute a posterior estimate of net flux. This suite of modeling tools can be used to attribute corrected carbon flux to specific processes including both human emissions and terrestrial and ocean exchange. Adapted from Bowman et al. (2017).

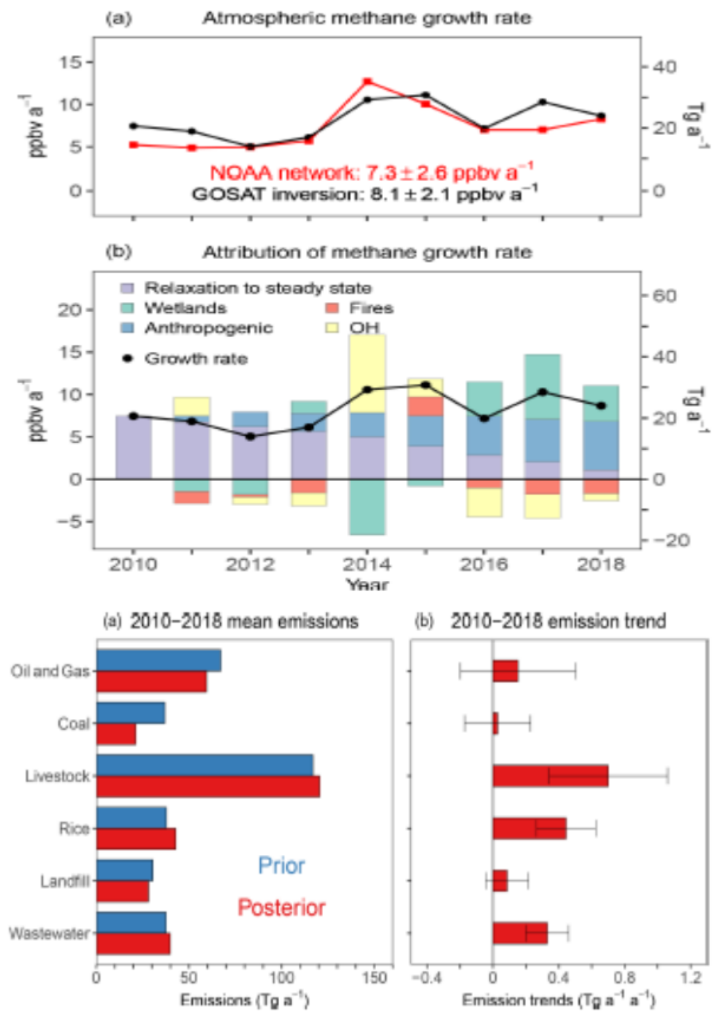

Figure 11: Attribution of the 2010-2018 trend in atmospheric methane by inversion of GOSAT satellite observations. The top panel shows the growth rates of atmospheric methane for individual years as measured by the NOAA surface network and as inferred from the inversion of GOSAT observations, indicating good agreement between the two and an acceleration of the methane trend after 2013. The middle panel shows the attribution of the trend to different sources and to the methane sink (OH), highlighting major contributions from anthropogenic sources and from wetlands. The bottom panels show the major anthropogenic emissions and their trends by sectors, indicating a major contribution of livestock to the methane trend. Adapted from Zhang et al. (2021).

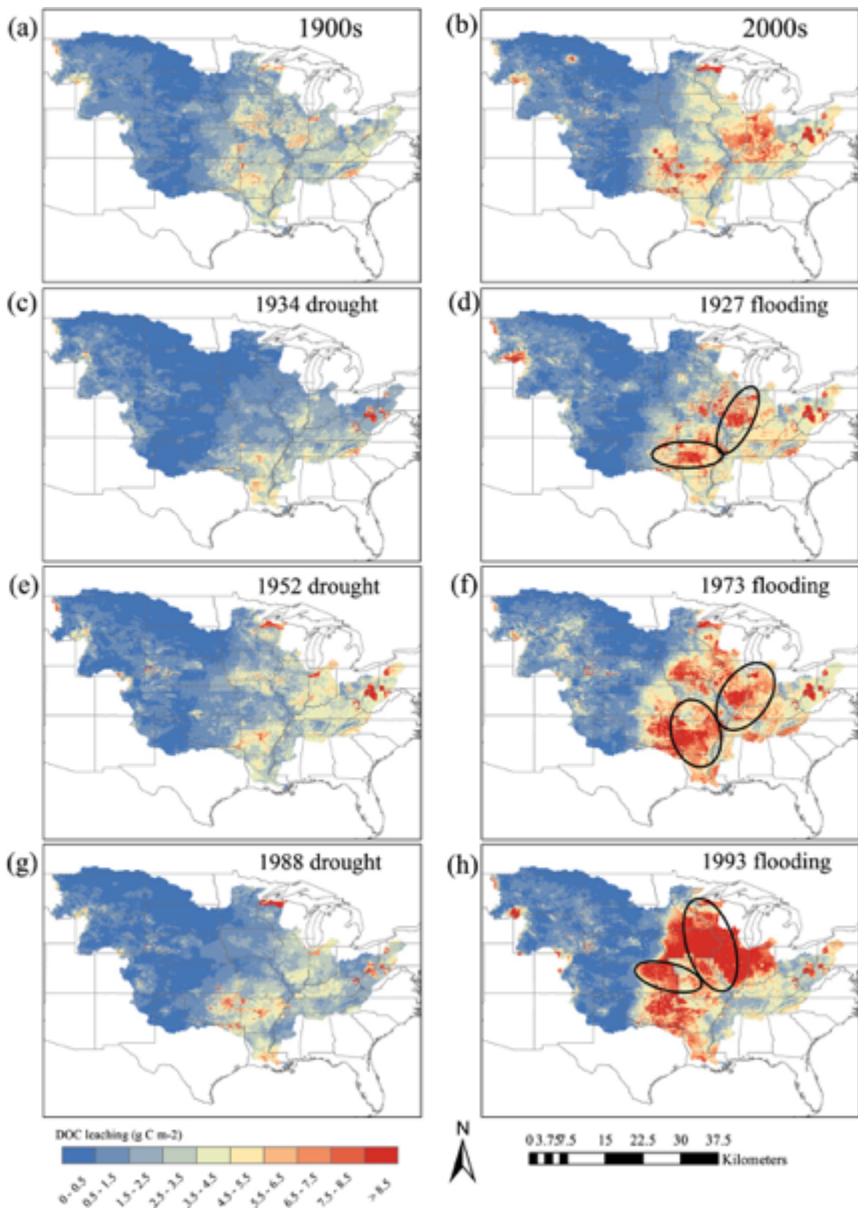

Figure 12. Century long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing (Renn et al., 2016).

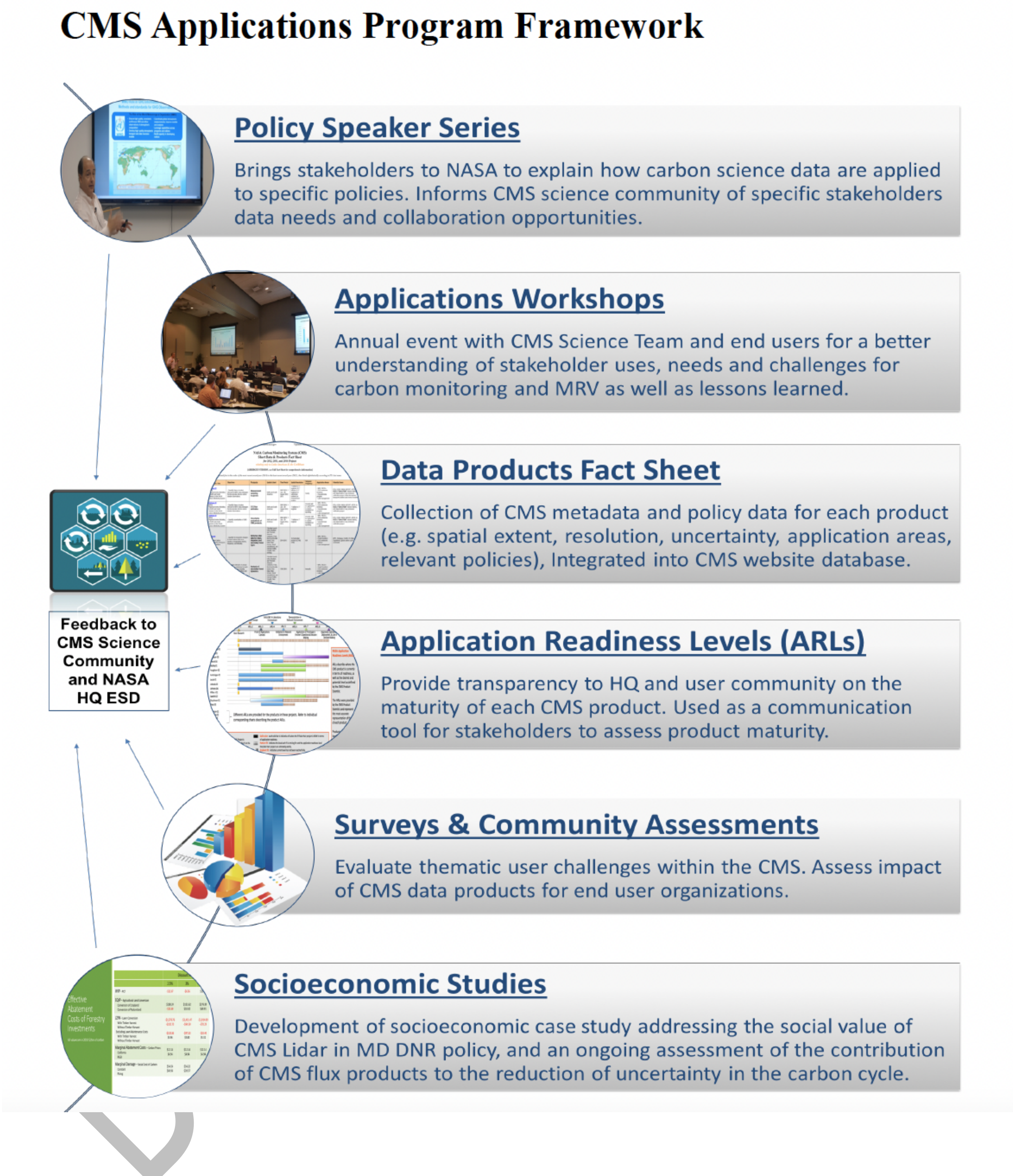

Figure 13. CMS Applications Program Framework for stakeholder engagement.

Supplementary Material

Geographic Domain	**Total Number of Projects**
Global	22
United States	31
North America	6
Brazil	4
Indonesia	3
Mexico	3
Asia (China and India) South America, Africa	1
Coastal West Africa, South East Asia, Indonesia, Ghana	1
Colombia	1
Colombia, Peru, Mexico	1
Gabon, Costa Rica, United States	1
Gabon, Tanzania, Mozambique	1
North and South America	1
Southern Africa	1
Tropical America, Africa, Asia	1
Tropical South America	1
Total	**79**

Table S1. Number of CMS Phase 2 projects by geographic domain.

Geographic Domain	**Total Number of Products**
Global	37
United States	60
Mexico	8
Gulf of Mexico	7
Indonesia	5
Brazil	4
Mozambique	4
North America	4
Canada	1
Colombia	1
Costa Rica	1
Latin America	1
Major River Deltas	1
Mexico and United States	1
Tanzania	1
Total	**136**

Table S2. Number of CMS Phase 2 products by geographic domain.

Domain	Flux Products	Land Biomass	Wet Carbon
Global	30	5	2
Continental	4	3	0
National	9	14	0
Regional	7	10	9
Site	10	27	6
Total	60	59	17

Table S3. The number of products by domain and theme.

Resolution	Flux Products	Land Biomass	Wet Carbon
100 ≤1000 km	15	1	1
10 ≤100 km	22	1	1
1 < 10 km	12	6	11
100 m – 1 km	1	7	
10 ≤100 m	1	30	
< 10 m	6	12	

Table S4. The number of products by resolution and theme.

	Flux Products	Land Biomass	Wet Carbon
Global	5.1 (5-9) (n=24)	5.7 (3-7) (n=3)	7.0 (7) (n=1)
Continental	7.3 (5-9) (n=3)	7.0 (6-8) (n=2)	N/A
National	7.0 (5-9) (n=7)	5.5 (2-8) (n=12)	N/A
Regional	4.2 (1-8) (n=6)	5.6 (1-9) (n=8)	5.7 (4-6) (n=9)
Site	3.2 (1-8) (n=4)	4.7 (1-8) (n=23)	N/A
All products	5.2 (1-9) (n=44)	5.21 (1-9) (n=48)	5.8 (4-7) (n=10)

Table S5. The average (and range) of ARL values by domain and theme.

*N/A refers to cases with either no products, or no ARL information.

Table S6. Biomass Summary

Scope:
- Pioneered use of remote sensing (lidar and optical) to map above ground biomass using a variety of approaches and across a variety of domains and spatial resolutions.
- Utilized remote sensing in ecosystem process models to enable future projections.
- Develop statistical tools related to biomass mapping from remote sensing.
- Partnered with a range of stakeholders to develop biomass data products to meet needs.

Findings:
- CMS projects have shown that biomass mapping is achievable at multiple scales, and that such mapping is defensible in the context of MRV and international carbon programs such as REDD+.
- CMS projects have advanced the statistical tools needed to make such mapping defensible.
- Biomass mapping has been achieved across a range of diverse ecosystems, and are applicable to new space-borne lidar missions such as GEDI. CMS studies have added to our understanding of the patterns of biomass, drivers of biomass change, and storage potential.
- Studies utilizing ecosystem process models have leveraged the high resolution lidar and optical data in to map both current stocks, and future storage potentials, for use in state level planning.
- Demonstrated highest levels of data product maturity (ARL 7-9) to state-level needs for some states.

Gaps:
- Although mapping of biomass has been successful, major areas of the world, including a diversity of different ecosystems, disturbance regimes, land-use activities, etc. have yet to be mapped or modeled or validated at high spatial resolution.
- For forest-related biomass mapping efforts, a key bottleneck and source of uncertainty is accurate quantification of the allometric equations needed to create reliable biomass reference data.
- Approaches are needed to scale from local/regional to continental and global domains.
- The spatial resolution and temporal mismatch of various datasets often complicates the fusion of these datasets together to inform C management efforts.
- Despite better inclusion of methodological uncertainties in estimation, it is unclear how to advise practitioners when uncertainties from different sources disagree on the same measurement.

Next Steps:
- Efforts must continue to improve biomass mapping over broad (continental to global) domains but at a fine spatial scale appropriate to capture variability in both natural patterning and in human interventions that drive change.
- Validation frameworks are needed to assess accuracy at a variety of scales against high-quality reference data.

- Novel approaches should be explored to help understand the influence of fine-scale variation on scaling efforts.
- Mapping should continue to improve the temporal cadence at which change in biomass can be tracked, thus allowing better attribution of changes to drivers over time.
- Additional process model-based biomass upscaling should be done, using a fusion of observation data and process models to infer biomass state and enable attribution and future projections.
- Clearer definitions of product uncertainties are needed.

Table S7. Flux Summary

Scope:

- Develop observationally constrained bottom-up estimates of fossil fuel emissions and land and ocean carbon flux from regional to global scales.
- Improve top-down estimates of carbon flux from regional to global scales including attribution to particular flux processes.
- Develop a variety of methods for quantifying transport and other sources of uncertainty in inverse flux estimates.
- Deploy new measurements to constrain and evaluate flux estimates at local/regional scales.
- Evaluate consistency and completeness of CMS products for estimating global carbon budgets.
- Ingestion of top-down estimates and ancillary into terrestrial ecosystem models to constrain carbon cycle dynamics.
- Improvement of fire-related datasets and prediction.

Findings:

- Global inverse models that incorporate satellite CO2 observations are able to reduce flux uncertainty and quantify the relative distribution of regional net fluxes. When combined with other types of observations, these models can also provide important information on flux processes.
- El Nino variability drives global CO2 anomalies through the tropical net carbon balance but with regionally distinct processes that are regulated by ecosystem memory.
- Current carbon monitoring systems are able to detect small (5-10%) decreases in global fossil fuel emissions related to COVID-19 and are consistent with independent country-level estimates of emissions changes.
- Bottom-up datasets provide more detailed information on key processes and trends (e.g. respiration, ocean phytoplankton composition)
- High-resolution, low-latency global flux datasets are needed to support atmospheric carbon monitoring.
- Regional networks of in-situ and remote-sensing measurements of greenhouse gas concentrations are capable of constraining and validating emission estimates.
- Atmospheric transport remains a sizeable source of uncertainty and characterization and reduction of errors is critical to success of inversions at both regional and global scales
- Fires are an important disturbance to ecosystems that drive regional carbon interannual variability, whose duration dominates global total burnt area, is sensitive to changes in climate, and are poorly captured by climate models.

Gaps:

- Lack of independent data at appropriate spatio-temporal scales for evaluating model-estimated fluxes, especially in the tropics.
- Satellite bias and coverage gaps limit both the accuracy and spatial scale of top-down global fluxes.
- Regional top-down estimates are limited by lack of boundary-conditions and transport errors remain a challenge for models across scales.
- Uncertainty estimates are difficult to interpret with different products and groups using very different methods.

- Large differences in bottom-up flux estimates persist despite incorporation of satellite data.
- Difficult to connect flux products to stakeholders (e.g. data formats, geographical boundaries, accounting definitions).
- Long latency of bottom-up products translates into even longer delay of top-down products which affects relevance to stakeholders.

Next Steps:

- Better integration of regional-global modeling activities (e.g. boundary conditions, consistency of transport)
- Integration of atmospheric flux, stocks, and disturbances into dynamical assimilation systems that can provide products that are both scientifically consistent and policy relevant.
- Scoping and support for new observations in support of regional flux evaluation
- Incorporation of multiple satellite CO2 datasets (e.g. GOSAT, GOSAT-2, OCO-2, OCO-3, GeoCarb) to improve net flux estimates
- Developing consistency in uncertainty methods that can be applied across bottom-up datasets, feed into top-down estimates in more meaningful ways
- Reducing latency in flux estimates.
- Integrated approach for engaging potential flux stakeholders, particularly at global scales

Table S8. Methane Summary

Scope:

- Exploitation of GOSAT satellite data to better quantify methane emissions and trends over the past decade.
- Development of improved process-based global methane emission inventories to guide inverse analyses of satellite data and understand emission trends.
- Local atmospheric measurement campaigns to quantify emissions on urban/regional scales.
- Guiding the design of the next generation of satellite instruments and retrievals.

Findings:

- Wetlands have likely been an important contributor to the rise in atmospheric methane over the past decade.
- Inundation and organic carbon respiration are major drivers of variability and trends in emissions from wetlands.
- Previous global anthropogenic emission inventories were seriously flawed, resulting in biases in inversions of satellite data.
- Trends in OH concentrations (the main methane sink) could have contributed significantly to the methane trend over the past decade.
- Future satellite instruments and retrievals can greatly improve our understanding of the atmospheric methane budget.

Gaps:

- There is considerable uncertainty in quantifying wetland emissions and how these emissions contribute to the global methane trend.
- The factors contributing to the global trend in atmospheric methane over the past decade are still uncertain.

Next Steps:

- Exploit the next generation of satellite observations of atmospheric methane to gain further understanding of the methane budget.
- Improved biogeochemical models for wetlands emissions are needed.

Table S9. Oceans/Wet Carbon Summary

Scope:

- CMS efforts have contributed to various efforts to better characterize the role of oceans and coastal interfaces in global carbon cycling.
- CMS projects have considered the nature of coastal margins as boundaries to the continental carbon cycle.
- CMS projects have examined the role of the coastal margins as net sinks or sources of carbon dioxide to the atmosphere. Considerable focus was given to the potentially large reservoirs of carbon biomass undergoing substantial change in sensitive coastal ecosystems.
- CMS projects have evaluated sources of methane and nitrous oxide emissions.
- Consideration by CMS projects was given to productivity and influencing factors in the Upper Great Lakes.

Findings:

- CMS efforts have greatly expanded the information about oceans and coastal interfaces and their key role in global carbon cycling.
- Coastal margins in North America act as a net sink of carbon.
- Impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins.
- Wetland and mangrove ecosystems represent important reservoirs of carbon and are undergoing rapid change.
- Wetlands may also be important sources of methane and possibly other greenhouse gases.
- Information about primary productivity in the upper Great Lakes was significantly expanded.
- An additional carbon related concern for coastal ecosystems is ocean acidification and its implications for coastal ecology and carbon cycling.

Gaps:

- Continued refinement of terrestrial ecosystem models is needed to reduce uncertainties in carbon flux quantification.
- Constraining estimates of contributions by coastal margins to continental and global carbon budgets requires improved assessments of exchange fluxes and the associated seasonal and interannual variability.
- Tidal wetlands and mangroves represent large reservoirs of carbon and are important as potential sources of carbon dioxide and other greenhouse gasses.
- Currently, knowledge is very limited regarding coastal margins as sources of methane or nitrous oxide.

Next Steps:

- Considerable progress in understanding contributions of coastal margins to global carbon, but this contribution is still not well constrained, particularly with regard to seasonal and spatial patterns.

- Need for coordinated modeling and observations across land-ocean continuum, including continued and expanded time-series observations to better discern temporal variability. Approaches should integrate observations, modeling and stakeholder needs
- Need for better quantification of methane and nitrous oxide fluxes in different coastal types (e.g., river, estuary, tidal wetland, mangrove, etc.).
- Need for continued advancement of novel approaches such as remote sensing techniques for characterizing changes in carbon biomass and fluxes in coastal environments.
- Uncertainties in feedbacks – how will future changes including climate, human impacts, and increasing atmospheric CO_2 affect efficiency of ocean uptake?
- Improved understanding of how coastal margins and associated carbon dynamics will change and what factors, including human activity, will influence that change will be important considerations for policy and decision-making.

Table S10. Stakeholder Summary

Scope:

- Worked with stakeholders to provide wall-to-wall, high-resolution estimates of carbon stocks, carbon sequestration potential, and their uncertainties over a range of domains and scales.
- Engaged a diversity of stakeholders, including:
  - Regional Greenhouse Gas Initiative (RGGI+) Engagement with state environmental managers from MD, DE, PA in 2014-17, then extending to MA, VT, NY in 2018-19, and to NJ, CT, RI, NH, ME in 2019;
  - CA Air Resources Board – methane emitters;
  - Other stakeholders include U.S. EPA, USDA Forest Service, Northwest Management, Inc., The Nature Conservancy, Environmental Defense Fund, Rocky Mountain Institute, BlueSource, Chesapeake Conservancy, Sonoma County Open Space and Preservation District, amongst others.
- Collected and analyzed stakeholder engagement metrics and product ARLs and connected them with drivers of ARL change.

Findings:

- Stakeholder engagement happens at the federal, state, and local level, as well as with universities, non-profits, private companies, and international partners. Examples include:
  - cities (e.g. Boston-DC corridor, Providence City),
  - state (e.g. Maryland, Delaware, CA, RGGI states),
  - international (e.g. Mexico, Indonesia, Mozambique),
  - WRI Global Forest Watch Tool.
- Stakeholder engagement focuses on bridging carbon science and user communities to better serve societal needs.
- CMS data products are used for GHG inventories, forestry, carbon markets, ecological forecasting, and climate applications.
- On average, stakeholders rate the value of CMS data products for their organizations very highly (8 out of 10). The ideal data format of products for stakeholders are .cvs or shapefile.
- Important characteristics of data needs by users include:
  - baseline estimates,
  - annual updates and information that describes change through time is needed for supporting decision making,
  - planning scenarios,
  - high resolution so that parcels can be managed and disturbance identified.
- There is great interest in methane monitoring and modeling products. Some of the products desired include: methane emissions at wetland scale; and high-resolution methane emissions to help identify fugitive emissions from sources like natural gas wells and distribution facilities.
- Information should be accessible via web and via accessible formats (geoTiff, csv).
- Finally, stakeholders would like carbon data for decision making that is easy to use and interpret, high-resolution, accurate, up to date, consistent year over year, pre-processed

and ready to apply for non-traditional remote sensing users, and that can be both downloadable and usable in an online interface.

Gaps:

- Change through time datasets, which require:
  - standardization and repeat acquisition of input data,
  - ongoing support of computing resources, access services,
  - transition of code to operational system along with financial support (e.g. NOAA CLASS system).
- Increase in spatial extent to support more users' policy needs, extending current datasets to new regions or ecosystems.
- More datasets on sensitive ecosystems – mangrove forests, urban forests.
- Economic studies needed to demonstrate value of information. Important examples to date
  - GCAM data documenting impact of carbon cycle uncertainty,
  - Maryland cost/benefit of forest policy.

Next Steps:

- Engage additional stakeholders to deepen and diversity applications across range oof scales.
- Sustained engagement is needed to get CMS data products used by decision maker.
  - Consistent and repeated dataset delivery beyond the end of the project, beyond the science funding to support use of datasets by decision makers.
- Data Tutorials needed for optimal use of CMS data products by stakeholders.
  - Stakeholders have expressed difficulty downloading and using some file formats, particularly .netcdf files.
  - Capacity building to understand, engage and extend carbon datasets to local, state, national and international institutions and individuals.
  - Stakeholders would benefit from tutorials on how to access, navigate, and download CMS datasets, as well as scenario-based exercises where they can learn of the different applications of some of the most used CMS datasets.
- More data needed in new regions and new ecosystems
  - Change through time, high resolution required to support decision makers.
  - New datasets linking biomass and methane emissions.
  - International forest initiatives that implement existing approaches in new states and new countries .
- Additional foci needed include:
  - reconciling carbon stocks and fluxes across multiple observations;
  - developing consistency across scales of similar carbon products;
  - attributing carbon emissions and sinks to respective sources, either point or distributed;
  - cross-sectoral accounting which is policy and regulatory driven;
  - uncertainty quantification across all products.

Table S11. Initiative Summary

Scope:

- Engaged a large and diverse set of scientists and stakeholders in prototyping novel approaches to carbon monitoring in all major components of the Earth System.
- Completed 79 projects prototyping the development of carbon monitoring products to meet stakeholder needs for biomass, flux, methane, and ocean/wet carbon.
- Engaged >130 stakeholders.
- Resulted in 482 publications and 136 archived data products.

Findings:

- High-resolution mapping of forest biomass enabled by LiDAR/Radar is now possible across a range of systems, at multiple scales and ARLs, and is defensible in the context of MRV and REDD++.
- Advancements in atmospheric inverse modeling techniques, analysis of climate drivers, development of new datasets, connections between projects and other data has led to important findings.
- Satellite and aircraft observations can usefully monitor methane emissions from the regional scale down to the scale of point sources.
- Coastal margins in North America and globally act as a net sink of carbon – high temporal and spatial variability. Impacts of human and climate-related forcing on terrestrial watersheds affect export of carbon and other materials to the coastal margins, and subsequently influence coastal carbon dynamics.
- Wetland and mangrove ecosystems represent important reservoirs of carbon and are undergoing rapid change, and may also be important sources of methane and other greenhouse gasses.
- Advancing science and addressing stakeholder needs are mutually beneficial. Stakeholder needs are extensive, and often alter/increase science requirements. Annual updates to describe change through time are needed. Very high spatial resolution needed for attribution and management. Address new quantities of interest from stakeholders. Improve information accessibility. CMS approach is a potential model for advancing and providing relevant science.

Gaps and Uncertainties:

- The mapping of land biomass and biomass change are yet to be accomplished with sufficient accuracy and resolution across all ecosystems, regions, disturbance regimes, land-use activities, etc. to meet stakeholder needs.
- It is not clear how different estimates of uncertainty can be reconciled, or combined, or applied, or how/how well various CMS products could be combined into global system level assessments.
- Challenges remain to continue to improve atmospheric flux products and their connection with stakeholders. Net fluxes from atmospheric data do not have clear stakeholder. Long latency and intermittent availability impacts relevancy for stakeholders. Lack of independent data hampers flux validation. Technical issues - data formats, geographic boundaries, accounting definitions can be improved.

- There is considerable uncertainty in quantifying wetland emissions and how they contribute to total national emissions and the global methane trend. Uncertainties in carbon respiration rate, inundation dynamics, non-growing season emissions all contribute. Different CMS studies suggest that wetlands, livestock, oil/gas exploitation, OH concentrations could all have contributed.
- Coastal margins are a substantial and highly variable signal in global carbon budgets, but this contribution is still not well constrained, particularly with regard to seasonal and spatial patterns. Limited work on aquatic, oceans, to date.
- Additional changes through time datasets and future projections are needed. This requires standardization and repeat acquisition of input data, ongoing support of computing resources, and model developments.
- There are many important science advances, partnerships, stakeholders, still needed to realize potential. New remote sensing assets, coordinated advances in computing and data, new partnerships and coordinated use of data from multiple sources/agencies, added stakeholders especially at highest levels.

Next Steps:

- Continue strategy of prototyping carbon monitoring capabilities to meet stakeholder needs across full range of systems, scales, quantities, stakeholders. Build on successes. Mature and scale-up existing successful approaches, and initiate new ones in areas, domains, most needed.
- Incorporate new remote sensing datasets (present-future) to improve and extend coverage of carbon monitoring capabilities. Expand the coverage of forest carbon monitoring and modeling capabilities globally (GEDI, ICE-Sat2). Exploit the next generation of satellite observations to constrain methane fluxes in a way that serves stakeholder needs (GOSAT, TROPOMI, etc.). Quantify impact on observing system flux estimates from integration of multiple sensors (OCO-2, GeoCARB, etc.).
- Continue emphasis on validation, and improve and coordinate quantitative estimates of uncertainties to facilitate interoperability of products and their applications. All products have estimates of uncertainties, but how to reconcile and combine different estimates, types, etc.?
- Develop integrated approaches for models and observations across scales, and across the land-ocean-atmosphere continuum, including continued and expanded time-series observations to better discern temporal variability. Increase focus on combining products/models for system level capabilities.
- Improve modeling capabilities and reduce model uncertainties. How can data be leveraged into models for greatest science benefit and stakeholder needs for future projections? How will future changes, including climate, human impacts, and atmospheric CO_2. etc. affect carbon stocks, fluxes, stakeholder planning? Advance models to use new data and meet needs.
- Mature and broaden system capabilities, including new partners and stakeholders to maximize quality, relevance, scale, and use of products. Add partners for added capability. Add stakeholders especially at the highest levels (global, national) for maximum relevance. Develop plan/approach to sustain advances once made

Table S12. Acronyms

- CMS - Carbon Monitoring System
- GEDI- Global Ecosystem Dynamics Investigation, NASA
- GOSAT- Greenhouse Gasses Observing satellite
- IR- Infrared Radiation
- MRV- Measurement, Reporting and Verification
- REDD+- Reduce Emissions from Deforestation and Degradation and foster conservation, sustainable management of forests, and enhancement of forest carbon stocks
- RGGI - Regional Greenhouse Gas Initiative
- ROSES- Research Opportunities in Space and Earth Sciences, NASA
- SWIR- Shortwave Infrared Radiation
- TIR- Thermal Infrared Radiation
- TROPOMI- TROPOspheric Monitoring Instrument